Autonomian

Unmanned Electrical Vehicles and Autonomous System Simulation

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Preface

This book and its offshoots were prepared to provide a comprehensive introduction into the domain of the autonomous system. The primary target audience is vocational schools and higher educational institutions running study programmes or modules on autonomy and autonomous systems. This book is also designated for teachers and educators willing to extend their knowledge and prepare a course on autonomous systems' technologies (full or partial).

The authors assume that persons using the content do possess some general understanding of IT technologies, including concepts of computing and computers, programming and software systems, and being exposed to high school mathematics. We believe that this book provides comprehensive and insightful material; however, it is not exhaustive nor an encyclopedia. The reason is the rapid development of autonomous technologies and their acceptance by the general public, which provides another development driver. Nevertheless, the book provides an excellent introduction and overview of the current state of the art technologies and insight into some of the core technologies related to today's autonomy and autonomou systems. We hope this book will let you find new brilliant ideas in your professional life and see a new hobby or even start an innovative business.

Note: Autonomous systems are there already; are you with us?

Project information

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1. Overview of autonomous systems

The essence of autonomy is one’s freedom to make a decision or self-government in its general understanding. In the context of technical systems, one can refer to a system’s ability to generate decision alternatives and select a decision on its own as a result of decision-making algorithms or other mechanisms. The field of robotics and intelligent systems has grown explosively over the last decade, and Unmanned Systems (UMS) are being fielded with increasing frequency in different domains including logistics, automotive, industrial cleaning, military and many more applications. However, as a consequence of this rapid advancement, a lack of agreed-upon standards, definitions, and evaluation procedures for UMSs exists. While a wide range of both autonomous and semi-autonomous UMSs are available for use, no measure yet exists to measure what the impact increased or decreased autonomy has on UMS performance. In other words, not always, it is obvious how the degree of autonomy correlates to performance, safety and usability of a given system. The following chapters provide an overview of the autonomous systems form different domains (application area) and particular technological specifics:

- Autonomous cars
- Unmanned ground vehicles
- Unmanned aerial vehicles
- Unmanned water and underwater vehicles (vessels)

1.1. Autonomous cars

Autonomous cars are among the most discussed and the most acknowledged technology is currently under development. However, as always happens with relatively new technology that has not reached its maturity, the existing terminology might be confusing. Currently one can face with definitions, which are inconsistent both verbally and semantically including autonomous vehicles (AV), self-driving cars, autonomous cars, robot cars, driverless cars, automated vehicles and others. Summarizing most of the available definition we will use the following (provided by SDC_Explained_2017)[1]:

Self-driving cars are cars or trucks in which human drivers are never required to take control to safely operate the vehicle. They combine sensors and software to control, navigate and drive vehicles.

Unfortunately, currently, there are no legally operating, fully-autonomous vehicles in the United States or other parts of the world. There are, however, partially-autonomous vehicles—cars and trucks with varying amounts of self-automation, from conventional cars with brake and lane assistance to highly-independent, self-driving prototypes[2].

Regardless of official announcements only a few of the companies are actually close enough to deliver a full-scale autonomous driving technology. At the time of writing this article, the most promising producers are: Waymo, GM Cruise, Argo AI, Tesla, Baidu[3]

If autonomously driven kilometres and a number of vehicles deployed (tested) are used as a general measure, them far ahead is the Alphabet subsidiary Waymo (https://waymo.com/), which works on the technology since 2009, when the Google self-driving car project was launched. Currently, Waymo reports 32 million miles driven in autonomous mode, what is more than any other “builder” has done. In terms of technology, Waymo uses all of the available sensors – cameras, Lidars, radars and even microphones to “hear” sirens of the emergency vehicles. The deployed autonomous cars are taxes in Phoenix (Arizona, USA). However, the “backup” driver can still be required due to safety reasons.

The technology behind includes the following main data processing steps:

- Mapping – the preprocessed map is required to build internal data structures and representation of the road infrastructure including traffic lights, sideroads and other important objects. The map is built by the company staff in 3D;
- Real-time sensor data processing, which enables to recognize and map surrounding objects like pedestrians, other vehicles, traffic light status, and others;

- Modelling – this step enables to forecast object motion patterns, what is of very high importance for safe driving;
- Decision making – taking into consideration of the mentioned aspects the control software determines the exact way of actions;
- Execution – the made decision is being executed on the road.

The second-largest autonomous vehicles fleet consisting of more than 180 vehicles is deployed by General Motors' Cruise division (https://www.getcruise.com/). The developing team puts a great emphasis on achievements in AI and robotics. However, a major part of the onboard hardware is made by the Cruise team as well.

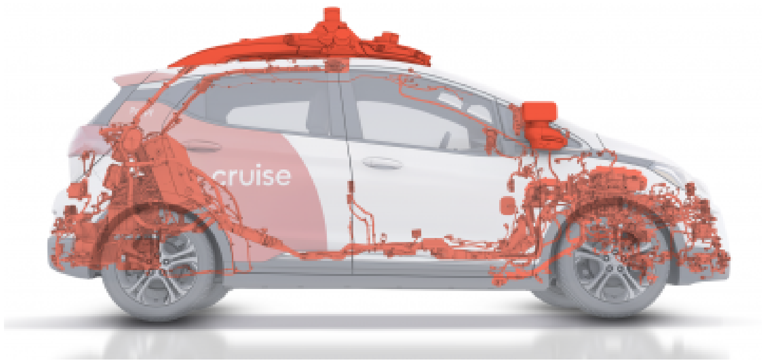


Figure 1. Cruise system

Figure 2. Waymo system

Similarly, to Waymo Cruise collects a lot of real-time data from Lidars, cameras, microphones, radars and other sensors providing a rich information source to machine learning algorithms and safety mechanisms. According to the Cruise reports, the used robotics algorithms provide decision making in millisecond scale enabling fast and proper response. For testing purposes data is being streamed to the development cloud and simulation toolset, which enables smooth access to data of the development team. The third-largest developer is the Ford Motor Company's startup ArgoAI (https://www.argo.ai/), which runs over 100 testing vehicles in at least six cities in the US. While currently retrofitting some existing vehicle models, Argo AI long term goal is to develop their own cars and produce them in masses. However, before consumer deals, the company follows B2B model for robo-taxis companies and other fleet management related services. Like other companies Argo AI a fundamental emphasis puts on safety, which is ensured through simulations in a virtual world in multiple scenarios at once. The sensor systems, in general, are the same – lidars, cameras, radars and microphone arrays. Among all others probably the Elon Musk's Tesla (https://www.tesla.com/) is the most discussed on the playground. Besides its financial and venture activities, probably the most interesting are some of the aspects of the used technology.

- Tesla's CPU (central processing unit – in a sense that this unit is responsible for the majority of data processing tasks and decision making) provides redundancy capabilities [CleanTechnica_2020]. Another important task is cross-referencing, which enables to minimize the impact of false decisions or miss-interpreted data.
- Another important feature is the lack of Lidars. The main emphasis is put on cameras (covering 360 around the vehicle), radars and advanced sonars.
- A deep reliance on machine learning – this one of the stated distinctive features of Tesla's technology at least as far as it is announced.
- Development is based on electric cars, not petrol inner combustion engines, which make the cars less effective and less controllable.

The latest but still being under development Tesla's hardware version is HW4 based on NVIDIA's systems. Despite bold promises of delivering fully autonomous cars by the end of 2020 at the moment of writing this page delivery are still on their way. However, still, Tesla's technology is considered among the most promising. The last but not the least is China's Baidu (https://www.baidu.com/ one might think of Baidu like China's Google), which has rolled-out back in 2019 for public tests and currently is running over 300 vehicles. At the moment Baidu runs robot-taxi service for test and advertisement purposes. Unfortunately, not much technical details are shared to the community, but some distinctive features are known, like vehicle-to-everything (V2X) technology as well as own hardware platform like Tesla has.

Besides the mentioned companies there are many more at different stages of development. However, the fundamental building blocks are the same:

- Self-awareness sensor systems like Lidars, cameras and others, which provide data for decision making in real-time under highly changing environmental conditions;
- High performance computing unit with redundancy and cross-check capabilities (not all of the developer ensures these capabilities yet);
- Simulation-based training before field tests, which reduces development time and increases safety;
- A great boosting effect could be smart-environments like smart traffic lights, which through intensive communications with vehicles increases safety and through the output of traffic system in general.

The main potential impacts of technology in the future is anticipated through the following main benefits [4]:

- Safety is the most anticipated with the potential to reduce the huge number of car crashes on a global scale. However, the main concerns are related to software security issues;
- Equity through enabling to mobilize people who currently because of different reasons cannot participate in mobile adventures. For instance, elderly people. However, this might have some negative aspects as well for instance, significantly increased traffic intensity, displaced employment structure and others;
- Environmental footprint which might shift to both – increased or decreased because of significant growth of total miles driven. On one case due to emissions, in the other due to the use of clean energy grids (for powering electric vehicles).

In the coming chapters, other types of autonomous vehicles are discussed.

1.2. Unmanned ground vehicles

Unmanned ground vehicles or UGVs are usually associated with ground robotic systems i.e. unmanned systems that are built for travelling ground surfaces. Depending on how autonomous systems is (autonomy levels are discussed later) the UGV might be both completely human operator-controlled via remote control link or autonomously operating system. In both border cases, the system itself is unmanned. Due to advantages over human-operated or manned vehicles in different applications domains, UGVs are rather widely used systems. The most common applications are related to domains, where it is convenient to replace human-operator or driver, due to safety reasons or hazardous operating conditions. Some typical applications domains are discussed below:

1.2.1. Military operations

This one of the most desired application domains, where human is a constant danger of being hit by hostile fire as well as being under highly physical conditions and stress. Therefore, remotely operated UGVs are rather commonly used by different armies all over the world. The main challenges being tackled is to remove soldiers from the line of fire i.e. while the soldier is undercover he can use remote control and operate an armoured or armed UGV. Thus, both soldier safety and operational goals are met. Unfortunately, due to the complexity of military operations and due to unstructured environmental conditions, fully autonomous system is yet to come. The majority of the military UGVs are fully remote-controlled, where human-operator is constantly looking after UGVs operation. A good example of military UGV is Milrem system (www.milrem.com) developed jointly by Estonian and Finnish companies, enabling different configurations, modularity and variable control options.

1.2.2. Logistics

In a logistics application, the majority of systems enables automated delivery of good within a limited territory – manufacturing plant or logistics centre. A widely known example is the result of cooperation between Kiva systems and Amazon, which resulted in Amazon robotics (https://www.amazonrobotics.com/#/). While there are several technology providers and still the challenge being tackled is the management of multiple logistic robots at once ensuring harmonized simultaneous operation. However, there are attempts to build outdoor logistic systems so-called last-mile delivery systems. A good example is the Starship system (https://www.starship.xyz/) provided by StarpShip technologies. The Starship solution provides the best of autonomous driving and remote control enabling flexible and relatively safe payload delivery within a limited territory. Currently, the solution is available in the USA and Estonia.

Figure 3. Starship last mile delivery system

However, to provide the best of the technology some legal prerequisites should be met including changes in road control rules. Another significant change is social acceptance which has to be led by a positive example and real benefits for society.

1.2.3. Industrial cleaning

Industrial cleaning is one of the areas that seem to be obvious to be enhanced by fully autonomous systems – cleaning robots. There is a major shift already and several producers have announced their products. Among them, some well-known brands within the domain might be noticed –
Nilfisk (https://new.nilfisk.com/global/campaigns/intelligent-cleaning/), Hako (https://www.hako.co.uk/machines/robotic-cleaning-equipment/),
Karcher (https://roboticsandautomationnews.com/2019/11/19/brain-corp-partners-with-karcher-to-develop-new-autonomous-floor-cleaner/26781/) and others. The technology itself not always

is developed by the producer itself. For instance, Brain Corp (https://www.braincorp.com/), develops autonomy technology but not cleaning machines. Therefore, mutually beneficial development is achieved. In terms of technology different approaches might be notices – a traditional approach, where robot control is achieved through real-time data acquisition, robot dynamics modelling and action planning, while Brain Corp relies more on machine learning. Thereby, one can see the same technology diversity as in the case of autonomous cars. Another challenge is the cooperativeness of individual robotic systems, which is also developed by several technology providers like Squad Robotics (https://www.squad-robotics.com/).

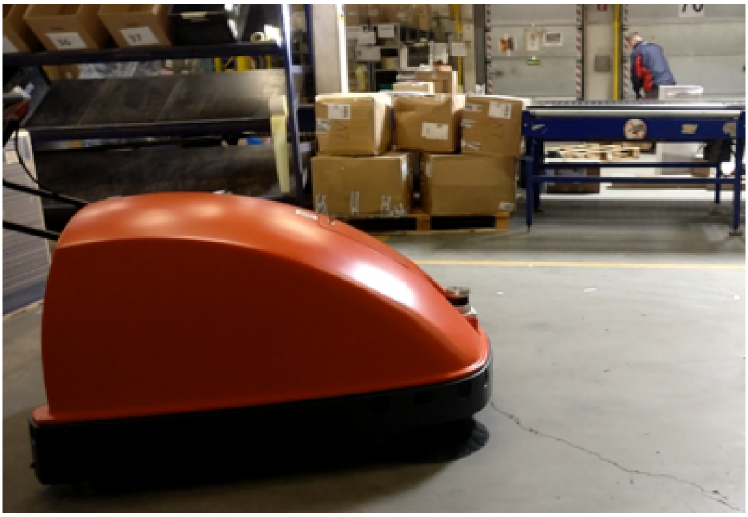


Figure 4: Autonomous industrial cleaning system in warehouse (SquadRobotics archive)

Cooperativeness is still among wanted but no yet available technologies in cleaning domain.

1.2.4. Agriculture / Horticulture

While agriculture seems to be one of the most mechanized and automated, in terms of robotics it rather weakly developed. There are a lot of discussions and research communities like ICT-Agri-food (https://www.ictagrifood.eu/) community, but still due to various reasons the number of deployed robots is insignificant. A good example is FarmBot system (https://farm.bot/), which provides the full cycle of growing vegetables at peoples back yard. Unfortunately, most of the systems being currently on the market cover only small fraction of whole food production workflow – transport, quality control, fertilization, harvesting or other limited functionality. This is a consequence of high complexity of the food production domain. However, among all of the application milking farm keeping is on of the most automated including feeding robots and cleaning roots that are fully autonomous – Lely automation solutions are among the most advanced currently available (https://www.lely.com/).

1.3. Unmanned aerial vehicles

Unmanned aerial vehicle (UAV) is an aircraft without a human pilot onboard. In a similar fashion as with autonomous cars or unmanned ground vehicles, depending on the level of autonomy (discussed later) the whole systems might use ground control station and vehicle operators that takes control over the system when necessary. The control system that enables UAV flying in autonomous mode is called – autopilot [5]. According to open sources (https://en.wikipedia.org/wiki/Unmanned_aerial_vehicle)

UAV systems according to their functionality and applications are classified using the following groups:

- Target and decoy – providing ground and aerial gunnery a target that simulates an enemy aircraft or missile. This one of the first applications used even in the Cold wartime;
- Reconnaissance – providing battlefield intelligence and ground data;
- Combat – providing attack capability for high-risk missions;

- Logistics – delivering cargo over the air, which usually is safer or faster than ground deliveries;
- Research and development – improve UAV technologies;
- Civil and commercial UAVs – agriculture, aerial photography, data collection.

To understand significant differences and challenges addressed by each of the UAVs group, they have to be looked closer.

1.3.1. Target and decoy

Flying target and decoy targets are among the first applications of unmanned aerial vehicles and historically goes back the Cold wartime when the first self-guided missiles were developed. For obvious reasons, the test targets had to mimic real target signatures, in every sense of this word, including shape, speed, manoeuvrability, electromagnetic reflection signature, thermal track of exhaust and other important features. These requirements and diversity of potential targets have facilitated the development of even higher diversity of UAV-targets and decoys – from small size low flying propeller aircraft to full-scale high-speed jet propulsion systems.

1.3.2. Reconnaissance

In military intelligence applications, the most valuable features are decreased visibility and extended remote sensing capabilities. However, not always it is possible to hit both targets. Therefore, most of the modern armies have intelligence drones of different sizes and flight schemas. For shorter ranges multi-copters that are specific with short flight time (~ 40 min.) and short-range remote sensor systems. For longer operation times fixed-wing aircraft are used like the one built by UAV Factory (https://uavfactory.com/en), which is a true market leader in the given segment – small fixed-wing drones. Fixed-wing aircraft can provide higher payload capabilities and higher energy-efficiency due to exploitation of aerodynamic forces. Currently, 24h flight time is rather widely available for this class of systems.

1.3.3. Combat

Combat UAVs are currently available in modern armies like the US as a solid part of conventional weapon systems. The impact on modern warfare is rather heavy changing not only tactics (regarding of richer intelligence available) but also strategies enabling to "fool" anti-air weapon systems and sometimes acting like a swarm of flying weapons. Some regional conflicts during the last decade show that combat UAVs might play the major role to take control over the battlefield.

For instance, Turkish Byraktars in Lybia [6]. If for a moment we ignore ethical and humanitarian consequences of using combat UAVs in masses, those machines are of extreme effectiveness like cavalry a few centuries ago.

1.3.4. Logistics

Using drones in logistics as a paradigm is not new, but still is not there. The most significant challenge is traffic control since the UAV systems will become a part of the air traffic and therefore both will bring new threats and opportunities at the same time. One can notice an obvious necessity for automatic traffic control systems instead of current human-operator based ones, which are of limited capacities and do no scale well. Some recent proposals have been made by NASA scientists [7]:

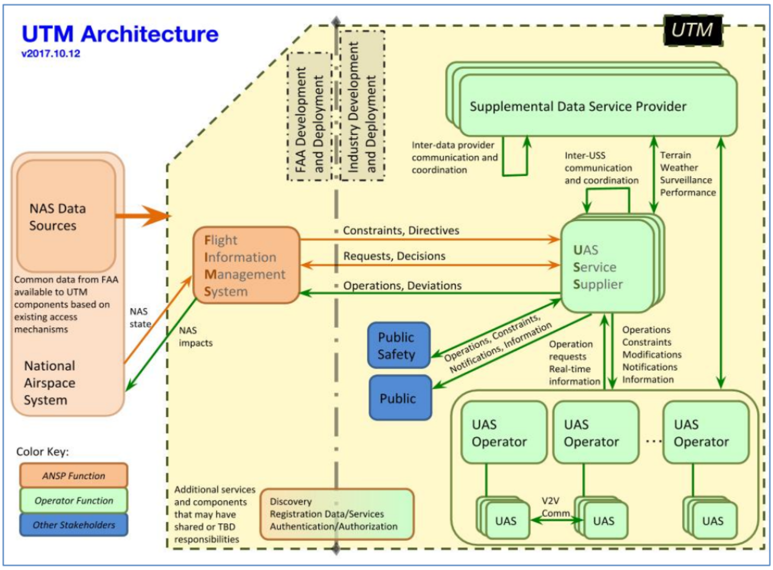


Figure 5. UTM Architecture

According to the proposed UTM (UAV traffic management system), the central element is Flight Information Management System or FIMS. Unfortunately, the technical solutions still are under development and communication standards are not there yet as well. Another important aspect is national regulations that have to be agreed in the same ways as done with regular air traffic regulations.

1.4. Unmanned water and underwater vehicles (vessels)

According to [8] Unmanned surface vessels (USVs) have also been called autonomous surface craft (ASC). As the name implies they remove the operators from the platform and allow new modes of operations. As global positioning systems have become more compact, effective and affordable unmanned surface vehicles have become more capable. Affordable, long-range and higher bandwidth wireless data systems have also been key to the rapid growth on USVs for many applications. Today USVs are widely used in military applications as well as scientific applications. Currently, all of the leading “sea nations” like Norway, US, Great Britain and others are working on their solutions for autonomous ships – water drones. A good example is the well-known Norwegian multi-sector company Kongsberg (https://www.kongsberg.com/maritime/support/themes/autonomous-shipping/#), which heavily invests in the development of digital solutions and autonomous vessel solutions. In the same way, as with ground and aerial unmanned systems, the main advantages of using unmanned systems on waters are reduction of the total cost of ownership, increased safety and higher flexibility of applications. The flexibility is exposed both through existing products and application potential in different fields including military, commercial and different civil applications.

1.4.1. Military

One of the first application domains is mine sweeping and mine laying use cases, what has been developed during the Second World War [9]. Currently, border monitoring, surveillance and security applications in the military domain are widely used as well. A nice example of security USV is Protector system (A Republic of Singapore Navy Protector Unmanned Surface Vehicle on display at the National Museum of Singapore as part of an exhibition called Because You Played A Part: Total Defence 30: An Experiential Showcase from 15 to 23 February 2014, commemorating the 30th anniversary of Total Defence in Singapore).

Figure 6. Protector system

Another good example of small size multi-purpose USV is Maritime Robotics (https://www.maritimerobotics.com/) Otter system (https://www.maritimerobotics.com/press?pgid=k8qc87da-0c15f7fe-07ab-4614-9ae7-26dfac6cce5a):

Figure 7. Protector system

In the same fashion as with UGVs, those systems are mostly remotely controlled due to security reasons and maritime domain regulations.

1.4.2. Commercial:

Commercial applications seem to be with the most social impact in the future since commercial systems might replace short- and long-range liners and ferries reducing total costs of ownership and increasing the overall safety on commercial waters. Again, among the main contributors might be Norwegian multi-sector company Kongsberg and various developer teams around the World. Currently, only very few test vessels are commissioned but there is a significant buzz round announcements made b the developers. Currently, the main challenges are related to safety and special operations automation, which are required in ports according to the acting regulations.

1.5. Autonomy

In the context of unmanned systems autonomy means the ability of a given system to operate without the attention of a human operator. Therefore, in an oversimplified way, one might think of a total operation time, where part of the time is done without human attention while another part in an unattended way. Depending on the proportion of the unattended time operation different autonomy levels and different operation requirements might be defined. The next chapter provides a deeper insight into autonomy levels and expected performance. The following topics are discussed n details:

- Autonomy levels
- Safety levels
- Ethics

1.6. Autonomy levels

Why one should worry about a particular autonomy level scale? There are several good reasons for this:

- Depending on autonomy level system owner might expect particular performance and functionality, as we do with technology readiness levels (TRLs) or other classification scales;
- Different regulations might be applied to systems of different autonomy levels;
- Sometimes it is necessary to forecast potential performance of the autonomous system for mission planning or design purposes.

Besides a plain autonomy level definition, several models have been proposed for assessing UMS (Unmanned Systems) level of autonomy and autonomous performance, and these models are briefly discussed in this section. Among the earliest attempt to quantify autonomy is [10] work on autonomy model ALFUS. The ALFUS is not a specific test or metric, but rather a model of how several different test metrics could be combined to generate an autonomy level. As it is depicted below ALFUS model uses three dimensions – Environmental complexity, Mission Complexity and Human independence to describe – are used to assess autonomy of a given UMS [11].

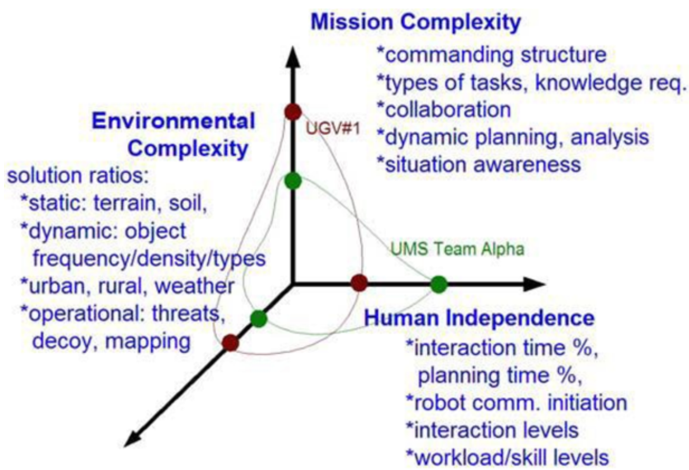


Figure 8. Alfus framework

The ALFUS framework provides the capability of estimating the level of autonomy of one robot or a team of robots. However, this methodology still has some drawbacks that prevent its direct implementation. The ALFUS methodology does not provide the tools to [12]:

- Decompose the tasks in a commonly agreed-upon, standard way;
- Test all possible missions, tasks, and sub-tasks;
- Assess the interdependency between the metrics, as some of the subtasks can apply to more than one metric;
- Allow metrics to be standardized in scoring scales; this will cause subjective evaluation and criteria to influence the results across different robots, users, or competing companies;
- Integrate the metrics into the final the autonomy level.

Partially ALFUS drawbacks are tackled by another – non-contextual assessment formally called the Non-Contextual Autonomy Potential (NCAP) [13]. The NCAP provides a predictive measure of a UMS's ability to perform autonomously rather than a retrospective assessment of UMS autonomous performance relaying on tests performed before the actual application of the system being assessed. The NCAP treats autonomy level and autonomous performance separately. A UMS that fails completely at its mission but does so autonomously still operates at the same autonomy level as another UMS that succeeds at the same mission. Model visualization is provided below:

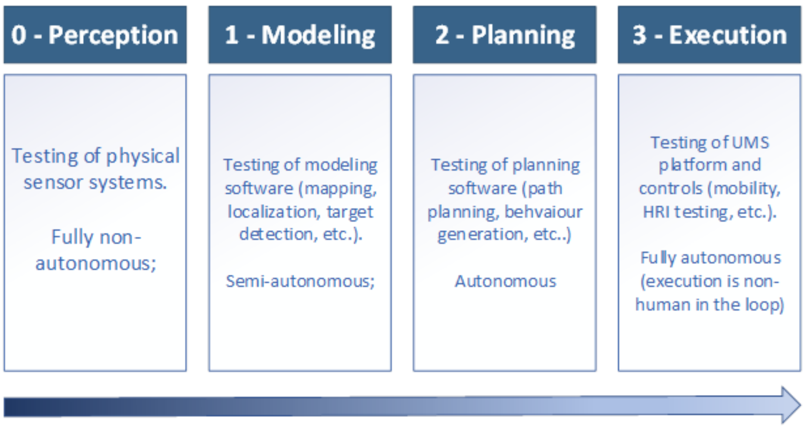


Figure 9. NCAP framework

As it is said in [14] the major drawback to these models is that they do not assess, specifically, the mission-specific fitness of a UMS. It might be a case when the user has several UMS assets available for a given mission or task, and the current models do not provide a simple answer for which asset is "best" Furthermore, none of the current model addresses, quantitatively, the impact on the mission-specific performance of changing a given UMS's level of autonomy. With this need in mind, a metric for measuring autonomous performance is designed to predict the maximum possible mission performance of a UMS for a given mission and autonomy level and is named the Mission Performance Potential (MPP). The major difference of the MPP model in comparison to the mentioned ones is defined by the following assumptions:

- not necessarily performance increases gradually if autonomy level increases. It means that ins some particular tasks the performance actually can drop;
- performance of the same UMS can vary from mission to mission. It means that the context of the system operation cannot be ignored during the assessment.

International Society of Automotive Engineers (SAE, https://www.sae.org/) have defined and explained autonomy levels of autonomous cars:

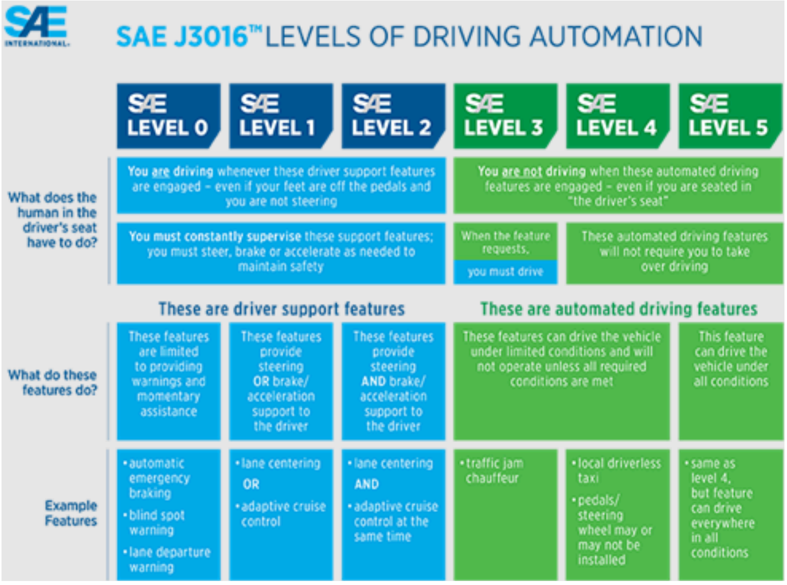


Figure 10. SAE autonomy levels

The SAE level definitions are more focused on product features to provide both better understanding of actual functionality of the automotive product as well as a foundation for legal regulations for each of the autonomy levels. In the context of Unmanned Areal Vehicles the autonomy levels are addressed by a little different classification while having the same number of autonomy levels: According to the Drone Industry Insights (2019. https://dronelife.com/2019/03/11/droneii-tech-talk-unraveling-5-levels-of-drone-autonomy/) there are 6 levels of drone operations autonomy:

Table 1. Autonomy levels (part 1)

Autonomy Level	0	1	2
Human Contribution to the Flight Control			
Machine (Drone Systems) Contribution to the Flight Control			
Flight Automation Degree	None	Low	Partial
Remarks	Remote Control (fully RC). UAVO controls the drone in 100%, manually (i.e. operator directly drives control surfaces).	UAVO in Control but the drone has at least one function it controls independently to the human operator (i.e. flight stabilisation).	UAVO is responsible for operation safety. The drone can take over controls given by the operator and modify it (i.e. heading, altitude hold, position hold, "smart" flight modes).
Environment Interaction (i.e. Collision Avoidance)	None	Sense and Alert UAVO	

Table 2. Autonomy levels (part 2)

Autonomy Level	3	4	5
Human Contribution to the Flight Control			
Machine (Drone Systems) Contribution to the Flight Control			
Flight Automation Degree	Conditional	High	Full
Remarks	UAVO acts as fall-back: the drone performs autonomous operation under given conditions (i.e. using preloaded flight plan). The Drone can introduce slight modifications to it. i.e. avoid collisions with detected objects.	UAVO is out of control here, the drone performs autonomous flight and is able to use its duplicated systems to remain safe and operable all time.	The drone performs fully autonomous decisions on the way they implement given task, using data and possibly AI to plan the flight and modify it.
Environment Interaction (i.e. Collision Avoidance) Sense and Avoid, usually also Alert UAVO	Sense and Avoid, usually also Alert UAVO	Sense and Navigate	

1.7. Safety

Safety of Autonomous Systems Working Group (SASWG) has identified a set of the most significant safety challenges considering the following aspects [15]:

- Domain-specific expert opinions on high-level issues within the domain;
- A set of modelled example systems and their possible use cases;
- Analysis of control software in autonomous systems;
- Analysis of experienced accidents – a small but representative set of accidents.

According to those considerations, the SASWG has defined a domain-specific safety topic to be discussed, considered or addressed by national/international regulations [16].

1.7.1. Air

- **Existing regulations** are well established and used for decades. However, this experience is not directly based on autonomous control software applications, which creates challenges to ensure software robustness.

- **Interface with Air Traffic Control**, which currently is based on verbal communication with Air Traffic Control operators. Autonomous systems will most likely require dedicated digital communication channels and protocols, which brings novel solutions with appropriate safety challenges;
- **Third-party risks**, which usually are related to the limited possibility to isolate third party systems. This creates risks of interaction, software updates, protocol updates, etc… As consequence regulations might be developed far too detailed creating risks of hard implementations and potential violation;
- **Reliance on external systems** is current practice. However, in case of malfunctioning of navigation systems like GNSS, there is always a pilot/operator, who takes over the control and uses visual information to navigate. In autonomous systems, this way of action might be problematic and therefore it creates safety risks;
- **Removal of human senses** as health monitors might be a source of additional safety risks since pilots usually get acquainted with the system they are operating. Removing pilot from the loop created risks of running into situations that are not properly recognized by automatic software systems.

1.7.2. Automotive

- **Assuring driver readiness** is related to different autonomy levels (see chapters on autonomy levels), where the human driver has to be ready to take over the control. However, the mains risk is related to the actual readiness of the driver for an immediate action;
- **Connectivity with other vehicles** and the environment might be required on different levels – individually with the environment, with other cars to platoon, with general traffic control systems. The communication mechanisms should be able to switch seamlessly between different modes. This is due to complexity, which brings additional risks of robustness;
- **Through-life behaviour monitoring** that due to autonomous operation might be a requirement. However, the data storage, collection and processing on third-party cloud systems, which brings risks related to proper data handling;
- **Behaviour updates** most probably will be a part of the exploitation of autonomous systems. Those updates bring several challenges:
  - B alance between recent experience and long-term experience not to lose important behaviours;
  - Balance between self and acquired experience from the cloud;
  - Software version inconstancy.
- **Value of simulation** might be overestimated replacing the real-world situation. Thereby the overoptimized software against simulation instead of real-world operation scenarios.

1.7.3. Defence

- **Mission** and its completion or non-completion conditions might be in a conflict with the safety requirements, thus compromising both during the decision-making process;
- **Test, Evaluation, Verification and Validation (TEVV)** are the key elements of designing highly assured systems. However, the trust might be related to technology acceptance with respect to methods used to formally verify performance and safety.

1.7.4. Maritime

- **Long communication paths** make difficult communication with operators or costal behaviour control systems, which defines overall risks or operation;
- **Limited monitoring infrastructure** due to specifics of the maritime operation might be not available for long distances, what requires autonomous systems to be resilient enough to be on a self-governing base for a needed period of time;
- **Weather** is one of the significant challenges in maritime operations since it is not avoidable by going away or around the stormy regions;
- **Hostile adversaries**, which have been a case in maritime operations history. It means that the proper behaviour of the autonomous systems under hostile actions are creating certain challenges.

Besides the regular safety issues related to electro-mechanical and control software system safety and reliability, autonomous systems bring new variable in the total safety equation – Artificial intelligence (usually in a form of machine learning algorithms). Unfortunately, the classical safety processes that are relied on risk quantification (Quantitative Risk Analysis – QRA) often are with significant limitation in the context of autonomous systems because of AI/ML applications [17]. The main drawback is of classical approach is the assumption that potential risks (tackled by safety procedures/processes) can be assessed prior to the actual action. Still, the central element of risk assessment is the case, which challenges the safety of the system or other involved objects – other systems or people. Since the autonomous system to a large extent relies on a constant evolvement of the system through heavy use of machine learning. Therefore, it is obvious that the safety procedures have to revise accordingly i.e. constantly. The safety cases according to [18] still are the central elements and have to be constantly updated in respect to the modelled world's state and sensed state. Thereby the general framework for safety assurance encompasses the main steps:

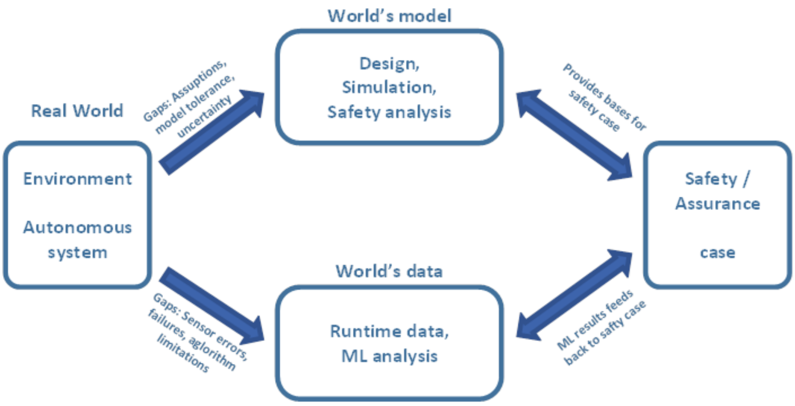


Figure 11. A general model for Safety assurance

- The "Real-world" is composed of the autonomous system and its environment including infrastructure and people;
- World's model is simulated world and safety analysis results within the simulation;
- World's data is composed of data sensed and results of data analysis ML algorithms;
- Safety case, in general, reflect the world's model cases, what are updated and tailored to the actual observations, thereby reducing gaps between model and reality.

1.8. Ethics

As has been emphasized earlier, autonomous system developers are under high market pressure due to high potential benefits within the particular application area. Artificial intelligence (AI) and its advancements are one of the main driving forces of raising ethical challenges. Most of the potential concerns have been arisen because of the latest advancements of autonomous cars, drones, social robotics and other technologies that have made some bold demonstrations and start to enter the consumer markets. The IEEE Global Initiative on the Ethics of Autonomous Systems, the United Nations, the International Committee of the Red Cross, the White House, and the Future of Life Institute are among many responsible organizations that are now considering the ramifications of the real-world consequences of machine autonomy as we continue to stumble about trying to find a way forward [19]. As it has been emphasized by [20] we develop technology faster than:

- understand implications of technology application in masses;
- interpret implications according to the current social and moral frameworks;
- develop and implement legislation and policies – global and national.

The mentioned concerns are especially actual in the light of hyper-fast development of AI technologies and algorithms that are already deployed and not always its users are aware of this.

Referring to [21] the main questions are:

- **In the context of autonomous cars: Who lives and who dies?** This is the most illustrative and probably the most discussed case i.e. in a case of inevitable car accident what decision for the control system of the autonomous car is the right one. Should the drive be put to the maximum risk to decrease risks of pedestrians or other traffic subjects or should it protect the driver no matter what? Another discussion is on legal aspects – who is responsible for making that decision and to what extent – drivers (car owners), engineers or somebody else? This comes to some legal issues as well, however, as a consequence another question arises – would it be a right decision to ignore or to obey some of the traffic rules in order to save lives or to decrease potential risks of a car accident? According to (Should a self-driving car kill the baby or the grandma? Depends on where you're from. | MIT Technology Review) researchers in MIT took an effort to study the question in more details through the experiment of a "Moral Machine", which tested situation on real people to answer a set of questions: should an autonomous vehicle prioritize people over pets, pedestrian over passengers, more lives over fewer, women over men, young over old, fit over sickly, higher social status over lower, law-abiders over law-benders. It turned out that the answer depends on various factors and is very different in different countries. Therefore another question arises – should the behaviour be tailored to a particular market? Unfortunately, those questions are still waiting for their answers.
- **Unordered List ItemIn the military context: Is saving the lives of civilians a moral imperative?** This question has been discussed by science fiction producers for decades – whether the machine should be granted the right to use lethal power against humans? From one point of view, those systems are already on the battlefields in a form of smart weapon and self-guided missiles. From another point of view – do that system really make decisions on using lethal power or decisions are still made by humans – solders? Unfortunately, currently non-combatant (people who are not participating in military conflicts directly) lives are not part of the decision-making equations at least on weapon systems. It means that the primary task is to hit the target rather than saving lives.
- **In the context of people intimacy: how close is too close?** In this context, intimacy is the subject of people being attached emotionally to a device – robot. One can refer to the AIBO (https://us.aibo.com/) robot or others of this kind. The trend is rather clear – the more advanced is technology, the higher the emotional attachment I will cause. So, what could be the consequences? What about human-human relationships on a broader view? Since most of those systems provide some kind of cloud data storages, the simple question is about what are the allowed methods of processing the data?

According to the defined questions, some others raise concerns caused by uncontrolled development of AI [22]:

- Unordered List ItemWill in general AI compete with humans, thus, compromising overall social constitutions and behaviour frameworks?
- As a consequence, will AI undermine societal stability? Here the main challenges are related to technology-led inequality as well as general shifts of the global economy due to digitalization.
- Will AI through better performing on data acquisition and processing harm privacy, personal liberty and autonomy?

To address the defined challenges organizations like IEEE have started discussions and put a lot of efforts in defining standards of "ethical" AI solutions, which obviously will change the overall landscape of autonomous technologies.

1.9. Technology

Since the application domains are representing a rather wide range of different systems at different levels of autonomy, it is obvious that technology behind the systems is diverse as well. However, each of the systems discussed has at least three fundamental constituents: Control mechanisms, Sensors and actuators. The basics of those constituents are discussed in the following chapters. The following topics are discussed in more details:

- Intelligent control
- Sensor technology

- Power sources
- Electric motors

1.10. Intelligent control

Control of a system is a set of actions needed to force changes in the system's state according to the set objectives, goals to be met and mission to be accomplished. Intelligence is brought by methods borrowed from Artificial intelligence including machine vision, decision making, learning and other methods. One can look at intelligent control and control in general through answers on the following questions:

- **Where the control decisions are made?** In the extreme cases: all of the decisions are made within the autonomous system - a fully centralized case or all of the decisions are made through distributed entities (other robots, cloud infrastructure, etc..) – a fully decentralized case. Both extreme cases do not fully exist now in terms of practically implemented systems. However, any proportion of both might create a different system architecture and specific technical solutions.
- **What decisions are made by the system itself?** Depending on the decision made by the system and by somebody else or something else, it is possible to implement systems of different autonomy i.e. more decisions are made by the system itself, a higher level of autonomy is granted to the system.

In the context of autonomy here, only the last question is discussed in details. According to [23] there are two main approaches to building control architectures – deliberative and behavioural architectures. All others are a kind of hybrids of the mentioned ones.

Deliberative architectures approach decision making by applying reasoning on a model of the world. Information flows in a sequential way from one module to another starting from sensor data acquisition, processing, interpretation, world's model update, action planning end execution. Rather classical architecture is NASREM (NASA/NBS Standard Reference Model for Telerobot Control System Architecture) [24]:

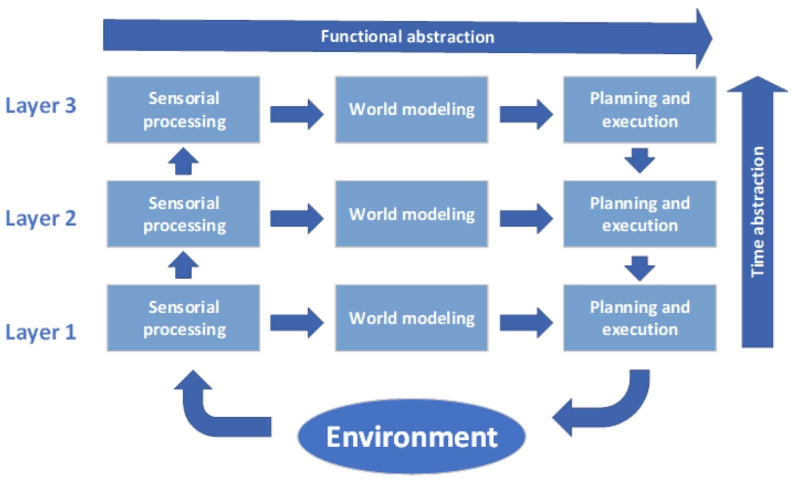


Figure 12. Three layer architecture

The lower layers respond faster than the higher ones to sensor input data. Data flows horizontally in each layer while control flows vertically. The architecture itself is not limited to three layers since it is a reference architecture.

Behavioral architectures follow the building blocks defined by [25], which are based on simplicity and assumptions to achieve low response latency:

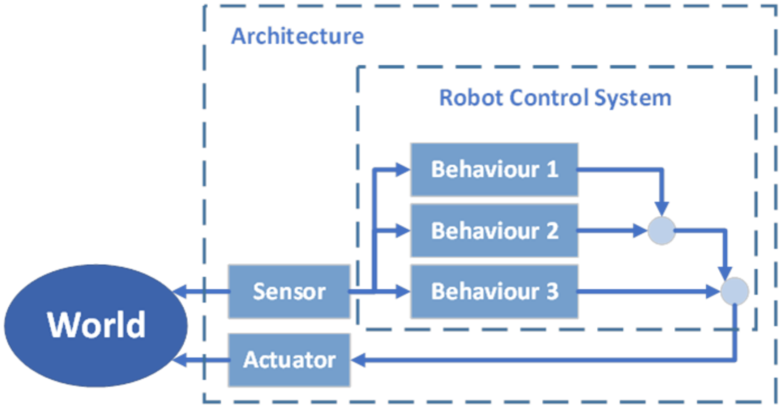


Figure 13. Behavioral architecture

In this case, intelligent control is achieved through asynchronous execution of different behaviours, which in their essence are finite state machines i.e. each behaviour is a separate module Thus, high flexibility and fast response are achieved. However, the drawback is an unclear reaction on conflicting behaviour results as well as high mission complexity.

Hybrid architectures combine the best of both deliberative and reactive (behavioural) architectures. However, the so-called – three-layer architecture is the most known one and combines reactive control at the lowest level and deliberative layer at the top level of the architecture:

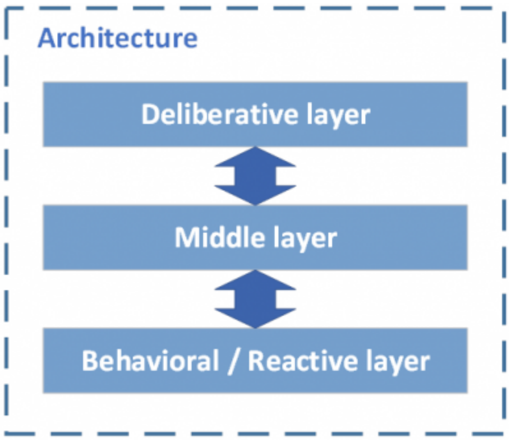


Figure 14. Hybrid architecture

- **Behavioral / Reactive layer** – reactive control, implementing and immediate action as a reaction to stimuli. For instance, if the autonomous system bumps into an obstacle it stops immediately.
- **Middle layer** – operational control, implements plan execution routines like obstacle avoidance, localization, mapping and other operational tasks. As with reactive control this layer processes sensor data and probably fuses it with other knowledge or data from the previous time window.

- **Deliberative layer** – strategic control, implements strategic planning and mission control tasks, like estimating how far the robot is from achieving the mission objectives. In many cases, route planning is implemented in this layer. This layer usually is associated with the intelligence of the system and the main indicator of the level of autonomy.

It must be emphasized that each of the layers whatever the architecture is selected might be implemented using a different software development approach, different methods and run on different hardware, which is a typical approach in the automotive domain to shrink response times and increase the overall safety of the system and its users. In military and space application different hardware allows increasing system's resilience.

1.11. Sensor technology

Sensors are used for estimating the state of the autonomous system as well as its operating environment. As shown in the chapter on intelligent control depending on particular architecture sensor data processing might vary from architecture to architecture, but all of them implement the simple **Sense-Decide-Act** cycle. In general, sensors provide information measuring the same phenomena as sensors of biological systems – light, sound, physical orientation, muscle stretch etc… In terms of information acquired by the sensor, they might be grouped into internal and external sensors, where internal provide data on the state of the autonomous system itself, while external sensors provide data on operation environment of the autonomous system. The most commonly used sensor types are discussed below [26].

1.11.1. Ultrasonic sensors

This group of sensors uses ultrasound waves and their feature of reflection from objects/ obstacles. Knowing the sound wave propagation time, it is possible to calculate the distance to the first obstacle on the wave's route. To do it, it is necessary to measure the time between emission and receiving time moments of the sound impulse. Therefore, the senor in its essence is a do-called time of flight sensors or simply ToF.

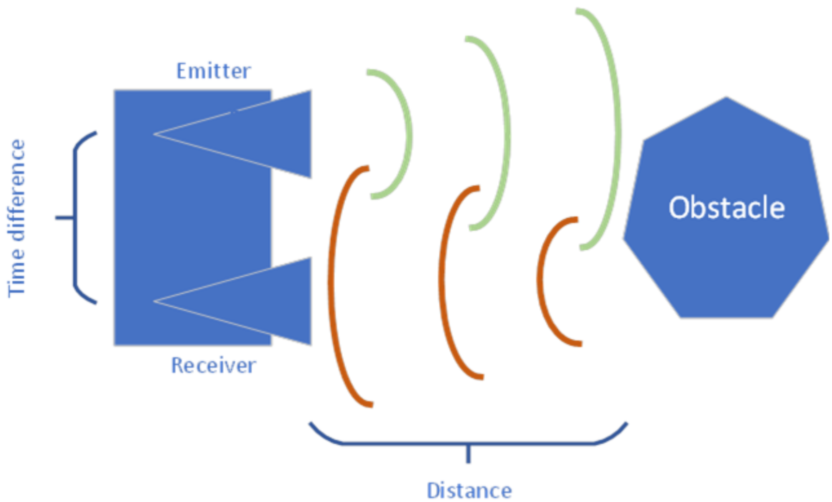


Figure 15. Sonar operation schema

Sonar sensors differ mainly by the wavelength of the impulse. Depending on particular configurations changes to distance and wave propagation speed of the impulse. It must be emphasized, that speed of sound is different in different environments (in terms of density), at different altitudes and different temperatures. Usually, time difference is measured by the on-board processing unit, that in more complex environments enables temperature and motion compensation of the sensor itself. These sensors are used as simple contactless bumping sensors or in more complex scenarios as "sound radars" enabling reveal high dualization of robot environment especially in high-density environments like water in underwater applications.

1.11.2. Lidars

Lidars (Light detection and ranging) sensors are very widely used in autonomous systems. In the same way, as sonars, Lidars exploit time difference. However, they might use other measuring techniques as well. Therefore, several types of Lidars sensors might be used in autonomous systems:

- **Pulse Lidars** use time of flight principle in the same way as sonars do. Knowing the speed of light gives enough information to calculate distance from the object hit by the laser ray. Another mechanism used in scanning lasers is a rotating prism, which enables to control the angle of the emitted laser pulse. Thereby both angle and distance might be estimated, which provides data to calculate the relative position of the object hit by the laser ray.
- **Continuous-wave** amplitude Modulated (CWAM) Lidars exploits phase shift of continuous intensity-modulated laser signal. In this case, the phase shift provides in its essence the same information difference of time when the actual phase has been emitted and observed.
- **Continuous-wave** frequency modulated (CWFM) Lidars mixes emitted and reflected signals using the principle of heterodyne via heterodyning (a method of mixing two frequencies). Using frequency shifts it is possible to estimate object motion speed and direction.

Other types of Lidars are derivates of the mentioned ones

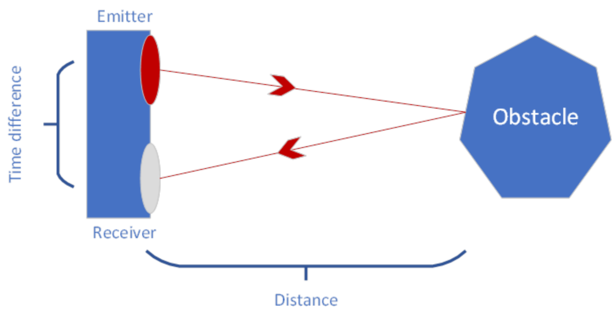


Figure 16. Lidar operation schema

Since the laser ray is very compact the sensing resolution is much higher than sonar sensors could provide. Another advantage is a relative energy-efficiency enabling the use of Lidars even to scan the object at significant distances. Currently, the market provides single beam Lidars, 2D/3D scanning Lidars. Currently, even 4D Lidars are in development to provide object motion data along with simple distance. This feature would allow capturing a very important piece of missing information, especially in the autonomous car domain.

1.11.3. Radars

Radars use radio signals and their features to estimate the distance to the object, its speed and direction of motion. Mainly two types of radars are used in autonomous systems – pulses radars and frequency modulation radars.

Pulsed radars in the same way as sonars or pulse Lidars, pulse radars use time difference of emitted and received signal pulses enabling to estimate the distance to the object detected.

Frequency modulated Continuous wave (FMCW) radars use frequency modulated signal, which might very from 30 GHz – 300 GHz. The emitted signal is mixed with the received signal to produce so-called intermediate frequency signal of IF. IF signal is used to estimate object range, speed and direction. Dedicated high-resolution FMCW radars are used to receive radar images enabling not only to detect but also to recognize the objects detected. Sometimes these radars are called broad-band radars or imaging radars. Currently mainly broad-band radars are used in combination with multiple receiving antennas enabling operation with different frequencies.

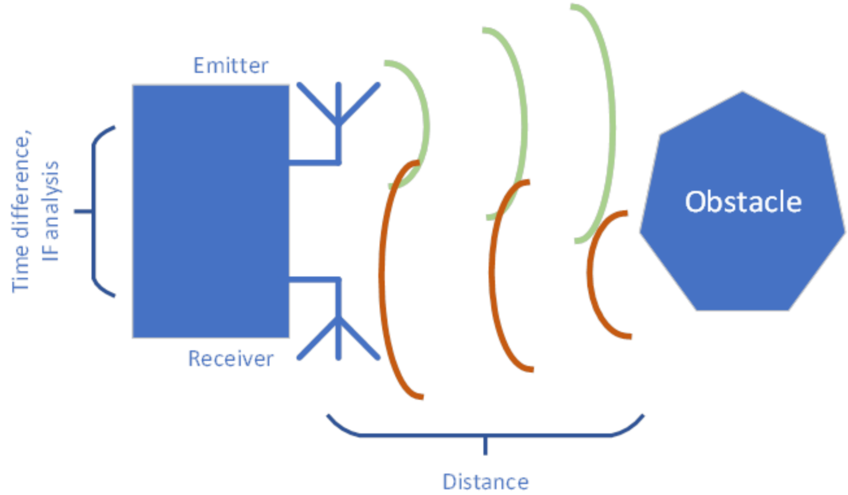


Figure 17. Radar operation schema

1.11.4. Digital cameras

Digital cameras, like web cameras, are used to visual information of the surrounding environment. It might be a simple solution as using a cell-phone and as complex as using stereo vision systems of time-synchronized cameras. Frame-based digital cameras are composed of lens and sensor matrix, where each element is called a pixel – a photo-sensitive semiconductor element.

Single-camera solution uses a single digital camera to obtain a series of frames, which enable to recognize an object in each frame, compare their position relative to the autonomous system and thus enables to estimate object relative speeds and displacements throughout the series of the frames. This is the most simples and the most imprecise solution due to imperfection of cameras, limited frames per second, sensitivity of the given sensor and other parameters.

Stereo vision systems are using two horizontally aligned cameras, which are time-synchronized (frames are taken simultaneously). Time synchronization minimizes the difference between frames. Horizontal alignment allows observing a distant object from a slightly different angle, which creates a slightly different frame. These differences – binocular disparity - allow to calculate point location in a 3D environment like the human brain does working with natural vision sensors – eyes. Acquisition of data of the third dimension requires additional calculations and inevitably additional computing power on-board.

Unfortunately, the mentioned systems suffer from several significant disadvantages:

- Motion blur – caused by motion and sensor sensitivity. The less sensitivity the higher blur effects might be observed. Blurred images decrease object detection and distance estimation precision;
- Lens distortion – distorts images in an unpredictable way as a result of imperfection of manufacturing;
- Frames per second – fewer frames per second, less accurate the derived estimates will be;
- Changes of light condition from one frame to another, which complicates the overall processing. One of the obvious results is changes in colours, which reduces the usability of the frames detected.

Event-based cameras allow avoiding all of the mentioned disadvantages at a cost of more complicated data processing. The essence of the working principle is similar to the natural light-sensing retina in eyes of biological systems, where only differences of light intensity are submitted instead of the whole frame. Thus, motion blur as a phenomenon and the related unwanted phenomena are lost. Therefore, the cameras might be an excellent option for visual autonomous system pose-estimation applications. Unfortunately, there is a price – algorithmic complexity of data interpretation.

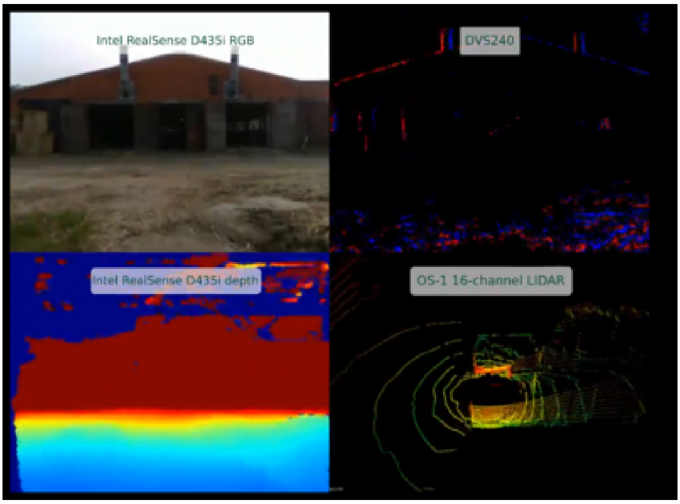


Figure 18. Multi-sensor imageS

Image is taken from experimental agriculture robot that uses multiple time-synchronized sensors – Single RGB camera (upper-left), Event-based camera (upper-right – reds pixels with increasing intensity, blue ones with decreasing), Lidar (lower-left) and stereo vision camera (lower-left). Image and video produced in ERDF 1.1.1.2 "Post-doctoral Research Aid", project num. FLPP Lzp-2018/1-0482.

1.11.5. Inertial Measurement Unit (IMU)

IMUs are the core of modern autonomous systems internal sensors, which uses different electronic devices to produce data of robot accelerating forces towards 3 axes as well as angular accelerations and angular positions. To do so, IMUs use 3D accelerometers, 3D gyroscopes and sometimes magnetometers. Today IMUs are exploiting different technical solutions, where the most affordable are MEMS (Micro Electro-Mechanical Mechanical System) systems. MEMS gyroscopes use lithographically constructed versions of one or more of the vibrating mechanisms i.e. tuning forks, vibrating wheels, or resonant solids of various designs [27]. This design uses the Coriolis effect – a vibrating body tends to maintain its vibration plane even if its supporting body plane changes (the autonomous system has moved). As a result, some forces are created to sensor bases, which are measured to determine the rotation rate. Currently, the most precise gyroscopic sensor available is fibre-optic gyroscope (FOG), which exploits the Sagnac effect [28], thus performing as a mechanical gyroscope. The basic principle is the use of two laser beams injected into a fibre optical channel with significant length (5km). Due to the Sagnac effect if the sensor is rotating one of the beans experiences a slightly shorter path, which results in a phase shift. The phase shift is measured using interferometry method, which results in angular velocity estimate. Despite various measuring methods, IMUs suffer from inherent problem – error accumulation, which provides a systematic error to pose estimation of the autonomous system. Therefore, usually in the outdoor autonomous system, additional sensors like GNSS (Global Navigation Satellite System) is used as an additional source of position information to mitigate the accumulation and keep in reasonable limits.

1.11.6. Rotary encoders

Rotary encoders are widely used in ground systems, providing an additional relatively precise and reliable source of displacement estimate. The main purpose of the sensor is to provide an output data on wheel or shaft angular displacement. There are two main types of rotary encoders – absolute and incremental[29]. As all sensors, rotary sensors have several main technologies:

- **Mechanical** – in its essence they are potentiometers, enabling to encode the full or several full rotations as a continuous output signal. Due to building principle used the sensor's main disadvantage is wearing out due to internal friction;
- **Optical** – it uses opto-pair to detect a reflected signal from the rotating disk (mounted on the shaft) or a light going through the disk trough dedicated gaps, thus providing a series of impulses while the shaft is rotating;
- **On- and Off-axis magnetic** – these types of senor use stationary or rotary magnets and exploit hall effect to sense changes in a magnetic field.

Using one of the designs absolute sensors allow to encode every single rotation angle with a unique code, while incremental produce a series of impulses. In case of incremental encoding usually a quadrature A_B phase shifts are used to determine both direction and displacement.

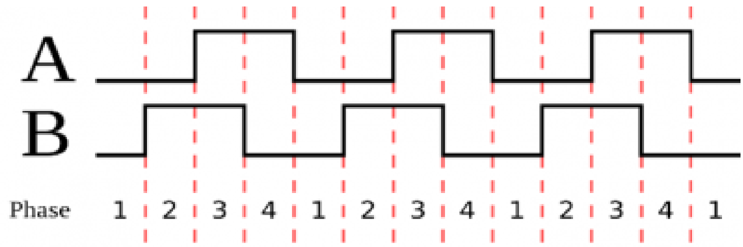


Figure 19. Rotary encoder time diagramm

1.11.7. SLAM

In autonomous systems, as discussed previously, sensors are used to acquire important data about the system itself and its surrounding environment, which is needed to make proper decisions. One of the fundamental needs in autonomous systems is keeping track of the system in a given environment. If environment's map is known then the task is to find distinctive features of the environment (corners, monuments, crossings, etc…) and knowing their relative position to the autonomous vehicle it is possible to locate the vehicle on the map using a technique – triangulation. However, in reality, a predefined reliable map is very rarely available. Therefore, the map has to be constructed during the exploration of the environment, i.e. the vehicle simultaneously constructs map finds its position on the map. This process is known as Simultaneous Localization And Mapping (SLAM). Depending on sensors used to acquired data about the environment as well as depending on computational resources, there is rather a rich palette of the algorithms available. Most of them try to employ a kind of data approximation to tackle the problem, which is clearly a – chicken and egg problem (what is first map or location on the map?). The overall process might be split into several steps:

- Unordered List ItemSensing the environment before any action is executed. This helps to acquire the first data and probably find there some distinctive features like corners in office or crossings in an open traffic application;
- Execution of motion which provides motion data from IMU, rotary encoders or other internal sensors, that provide data on the actual motion of the system. One might imagine this step as moving for short enough time with closed eyes;
- Location calculation and map update this step is the most complicated since it combines the map data acquired before, with sensed motion data and uses this data to update the map.

Implementation of the last step is the essence of all SLAM algorithms. Since the sensors provide data with some error due to imperfection of the sensor, the lasts step is done based on some kind of posterior probability estimation of the vehicle pose and for the parameters of the map. Algorithms differ in their way to use some statistical estimates or non-statistical estimates. Other pose approximation methods achieve improved computational efficiency by using simple bounded-region representations of uncertainty. Using even a single 2D scanning Lidar system autonomous vehicle could produce a map like this one:

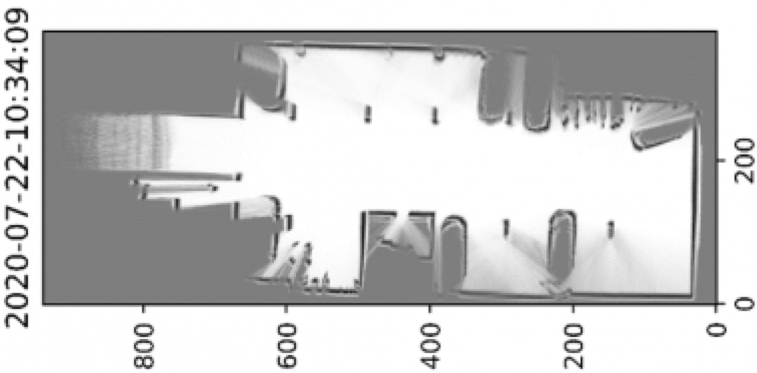


Figure 20. Map produced by a 2D Lidar system

Of course, not always the selected algorithm and its implementation provide enough precision, which might end up with maps far from perfect, like this one:

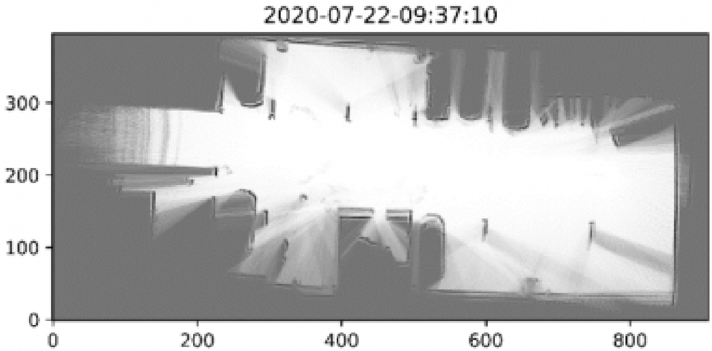


Figure 21. Imperfect map produced by a 2D Lidar system

Sometimes significant development time is spent on tuning parameters of the algorithms to get the best possible result for a given application scenario.

1.12. Power sources

There are two main battery types: single-use - **primary** and rechargeable - **secondary**. Electric vehicles (EV) and most of the other autonomous systems use secondary batteries (except for small toy vehicles and special applications) hence in this chapter the term battery mean secondary battery unless noted otherwise. From an economic perspective, batteries are a serious business approaching 100-billion-euro market size. About a third of all batteries are used as automotive traction batteries (EV, HEV), other third is used in industrial applications and portable applications (consumer electronics) while the last third is used in other applications like power tools and conventional car batteries. From everyday knowledge, it is known that batteries have different voltages. A wall clock typically uses an AA or AAA size 1.5 V battery while a car has 12 V lead-acid battery under the hood. There are two reasons for different battery voltages: chemistry and series connection. The chemical composition of battery materials determines the voltage in the range of 1.2 V to 3.9 V. How come a car lead-acid battery has 12 V? It actually has multiple smaller batteries inside and they are series-connected (mind the polarity) to sum up their voltages. These individual internal batteries are called cells. Figure 1 shows some multi-cell batteries. It would be technically correct to say that a battery is in fact two or more series-connected cells of the same kind. Hence a battery composed of just a single cell would not be a battery but rather just a cell. However, to not cause confusion it is accustomed in everyday language to use the term battery for any number of cells while a cell means a single element. This notation will be used here as well. One of-the-shelf battery is the car lead-acid battery which has six 2.1 V cells inside (the voltage is rounded to 12 V for convenience), another multi-cell battery example is the 9-volt battery which is composed of six 1.5 V cells (alkaline or carbon-zinc chemistry). When one installs two AA batteries in a TV, remote, they are series-connected to form a 3 V battery.

Figure 22. From top left: car 12 V lead-acid battery (6 cells), cordless drill 14.4 V NiCd battery (12 cells), laptop 14.4 V Li-ion battery (8 cells), special-purpose medical equipment 7.2 V NiCd battery (6 cells), memory back-up 3.6 V NiMH battery (3 cells), 18650-size Li-ion 3.6 V battery (single cell), generic AA size 1.5 V primary battery (single cell), disassembled 9 V NiMH battery (7 cells).

In electrical engineering, a battery is recognized as a voltage source. A major difference is that the voltage of this source will gradually decrease when a load is applied (discharge) while connecting a battery to a higher voltage source will cause its voltage to gradually increase (charge up). A more precise definition claims that a battery is in fact an electrochemical device which can provide voltage and release electrical energy stored inside of it in the form of chemical bonds.

1.12.1. Technical parameters

Voltage

The chemical composition of electrodes defines the voltage of a single cell. All types of battery cells have a certain nominal voltage Unom. As previously noted, the nominal voltage of different chemistries is in the range of 1.2 V to 3.9 V. The nominal voltage is somewhere between maximal voltage Umax (charging voltage) and minimal voltage Umin (discharge cut-off voltage, end-of-discharge). The nominal voltage is used for calculations to determine the voltage of the battery pack if cells are series-connected. Discharge cut-off voltage is the voltage beyond which discharge should be terminated to prevent damage to the cell. A battery discharge voltage curve is given in the figure below. For primary batteries, it is desirable to have a flat curve which translates to the stable supply voltage.

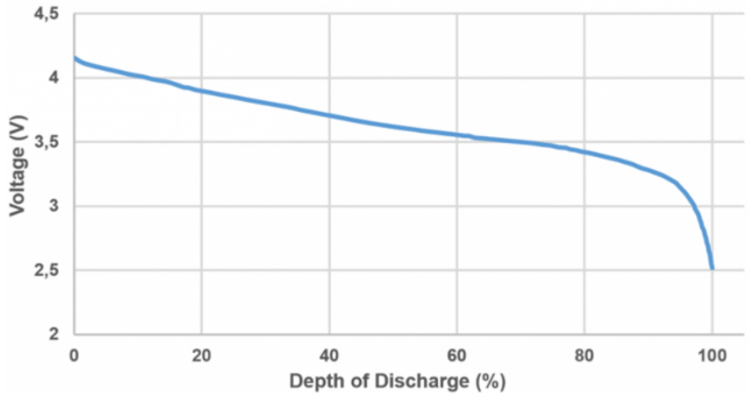


Figure 23. Discharge voltage curve of a single Li-ion cell: voltage decreases as the DoD increases

Capacity and energy

The second most important quantitative battery parameter is capacity Qbat. Capacity determines how much charge a battery can store. It is measured in amp hours (Ah). Higher Ah rating means the battery will be able to run longer before requiring a recharge. If the load current Iload is known then the runtime t can be calculated as follows:

$$t = \frac{Q_{bat}}{I_{load}} \qquad (1)$$

Figure 24. Runtime equation

Current and C-rate

The next electrical parameter is current. A good battery datasheet will provide at least a few current values at different conditions. Common parameters are standard charge current, rapid charge current, max. continuous discharge current and standard discharge current. Often the charging current ratings are significantly lower than discharge ratings. In engineering and battery datasheets there is another battery-specific parameter which is directly related to Ah rating: the C-rate. The value of 1 C is a number same as the nominal capacity of the battery. The C-rate itself has no unit of measurement but when it is converted to current it is expressed in amps A. C-rate is used to determine current for both charge and discharge. It comes handy when comparing current capabilities of different batteries and simply estimating how large the current is with respect to the capacity of the battery. For example, 2 C discharge rate of a 10Ah battery is 20 A while 0.5 C charge rate of the same battery is 5 A.

Cycle life and ageing

Battery lifetime is a critical parameter of secondary batteries. Depending on the chemistry battery lifetime is affected by ageing mechanisms: cyclic ageing and calendar ageing. As the name suggests calendar ageing is related to the absolute age of the battery: as battery ages, its performance will deteriorate – capacity will decrease and internal impedance will increase leading to decreased current capability. The other ageing mechanism – cyclic ageing, is related to the intensity of battery usage. A full battery cycle is a full charge followed by a full discharge. Battery manufacturers in battery datasheets give an estimated cycle life – typically few to several hundreds of cycles. For this cycle number to be true it is of importance to follow a specific charge and discharge test pattern: the manufacturer will specify exact charging and discharging current, exact charging and discharging cut-off criteria and exact rest periods between each charge and discharge as well as the ambient temperature (typically 25 °C) at which the battery should be cycled. A key fact is that batteries degrade with each cycle even if the cycle is not full. However, this degradation rate and linearity are not the same for all models.

Battery pack

As previously described, a battery pack consists of cells and a set of auxiliary components. Both in literature and practice, the word "pack" is often omitted as is here as well. For stationary applications, there is a term "battery energy storage system", which basically is a battery pack with additional interface converter which takes care of voltage conversion, charging and SoC (System on Chip) control. Each battery module or a small battery pack consists of individual cells. All cells are of the same model and are preferably parameter-matched to provide maximum performance utilization. There are two types of connections which can be used to combine individual cells: series connection and parallel connection. In a series, connection cells are connected in a string so that the positive pole of one cell is connected to the negative pole of the next cell. The voltage of a string is the sum of individual cells. n is the number of series-connected cells.

$$V_{string} = V_{cell1} + V_{cell2} + \cdots + V_{celln} = n \cdot V_{cell}$$

Figure 25. Voltage of battery string

In a series connection, the capacity rating (Ah rating) stays the same as for a single cell. In a parallel connection, all positive poles of all cells are connected together, and all negative poles are connected together as well. The correct polarity is of utmost importance as the incorrect polarity of a single cell will cause an immediate short circuit which in the worst case can result in fire and/ or explosion. The total voltage of a parallel connection is equal to that of a single cell. Parallel connection affects the total capacity which can be calculated as the sum of combined cells.

$$V_{parallel} = V_{cell}$$

Figure 26. Voltage of batteries in parallel

As the capacity rating is increased, the C-rate is increased proportionally as well, resulting in higher permissible

One of a battery pack's description parameters is the cell configuration: how much cells are connected in series and how much in parallel. A thirty cell series connection is described as the 30S while ten cell parallel combination is described as 10P. Both parts are typically combined: 30S10P – the battery pack consists of 30 series-connected cells and each "cell" is made of 10 actual cells in parallel. This pack contains 300 cells in total.

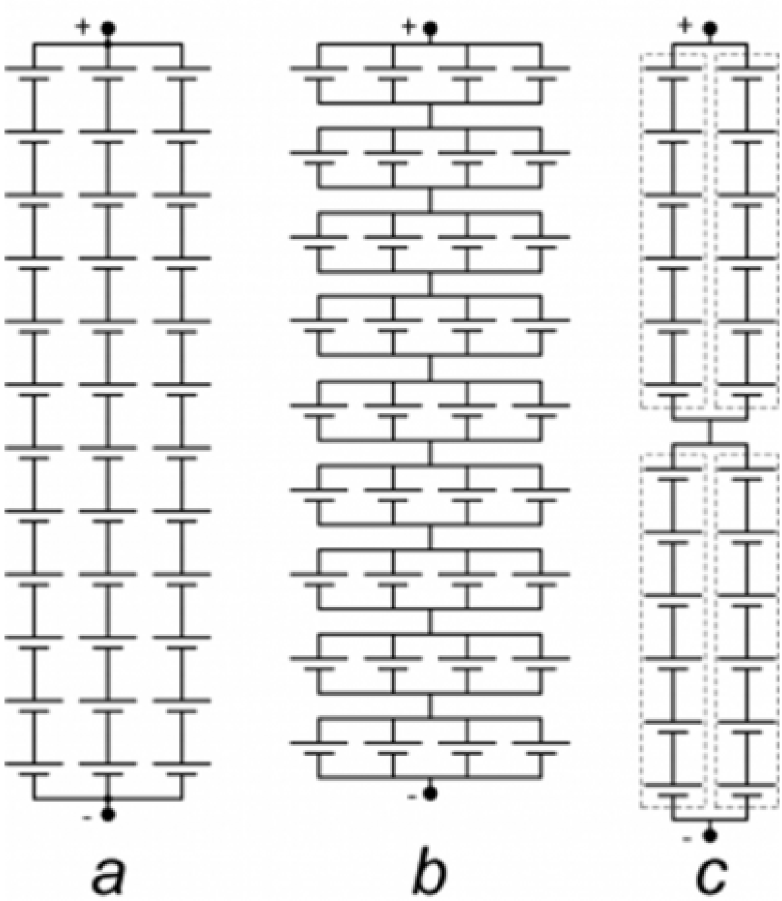


Figure 27. A: series first 3P12S battery; b:parallel first 9S4P battery, c:a mixed connection battery pack where each dashed box could be an 6S1P (12 V) lead-acid battery hence total configuration could be labeled as 2S2P.

Battery management system (BMS)

Sometimes even a single cell requires an obligatory BMS, which can have a variety of functions. The main task of a BMS is to maintain a safe operation of the battery – the safety of Lithium-based ell has always been an issue, which requires special care. The functions can be divided into four groups: protection, monitoring, estimation balancing. Safety essentially is protection. Some cells have some inherent safety features, such as overpressure, short circuit and thermal protection. The thermal management system can be a part of the overall BMS. Battery packs can be actively cooled (or heated) – the temperature of coolant medium and its flow must be monitored as well. BMS monitoring functions might include data logging of all mentioned measured parameters and additional ones like total cycles, max and min discharge levels, total delivered energy and other time and charge related variables. BMS and its functions can extend further. As mentioned, thermal management can be a part of BMS, especially if active temperature control is used: forced-air or liquid cooling/heating. In EVs charging is controlled by the BMS as it has information about charging voltage, current and can provide temperature and safety control. BMS has a communication interface to the main vehicle control system. Some sort of charger is usually implemented in an EV and in some cases, the charger is a part of the battery pack. EV batteries are equipped with fuses and set of contactors: for work current and precharge. Smaller batteries can have some human-machine interface (HMI), for example, a set of LEDs, to indicate remaining charge. All of these features are controlled by the BMS.

1.12.2. Fuel cell technology

Fuel cells (FC) are devices somewhat like batteries. Their purpose is to provide electrical energy by converting chemical energy. Same as batteries they are electrochemical devices. The main difference is that fuel cells use some sort of chemical compound (fuel), which is supplied to the cell to produce electricity by a controlled electrochemical redox reaction. The fuel and oxidizing material (oxygen from the air) is consumed during the process. On the other hand, the battery already had all components embedded in a closed package and no material was consumed during charging/discharging. Fuel cell technology has a long history as it was invented in the 19th century. Since then various configurations have been developed and implemented in stationary or portable applications ranging from few Watts of power to mega-watt systems.

The most notable fuel cell technology is the proton exchange membrane fuel cell (PEM FC). The basic elements of a fuel cell are anode, cathode and electrolyte. A PEM layer contains an electrolyte and separates the anode from the cathode. Fuel is delivered to the anode side while oxygen is delivered to the cathode side. Popular fuels are hydrogen and methanol. As an electrochemical reaction takes place, protons from fuel are transferred through the PEM to the cathode side where waste is produced: water in case of hydrogen fuel and CO2 if methanol FC is used. As usual, the electrical load is connected to anode and cathode to deliver electrical energy. Common efficiencies are in 50 to 60% range which means that significant amount of heat will be generated during power production – a cooling system like one of the common ICE vehicles is required as the temperature operating range of FCs is limited.

A key issue for hydrogen FC adoption is the lack of refuelling infrastructure. Hydrogen gas is extremely flammable, it can diffuse in and through metals and it can cause metal embrittlement hence manufacturing, handling and storing hydrogen requires additional care. The final problem is the source of hydrogen. The amount of hydrogen in the atmosphere is negligible hence it must be manufactured. It can be produced by electrolysis of water however this process is inefficient even further decreasing the total FC technology full-cycle efficiency. Currently, the majority of hydrogen is produced by reforming fossil fuel – not a sustainable solution. Despite these drawbacks, hydrogen FC technology has been and is used in some commercial EV products. There are a few available automobile models and several public transport buses. The later has shown good performance as buses have stable cyclic usage and plenty of space for FC and hydrogen storage tank installation.

1.12.3. Supercapacitors

In simplistic terms, supercapacitors (SC) are capacitors with extremely high capacity. In fact, they use special physical effects (electrochemical pseudocapacitance and/or electrostatic double-layer capacitance) to provide capacity. Depending on brand-names and physical effects, supercapacitors are also called boost capacitors, ultracapacitors, pseudocapacitors and electrostatic double-layer capacitors (EDLC). One must not confuse SCs with common high capacity aluminium electrolytic capacitors which are made with rated voltages from few to hundreds of volts. The rated voltage of a single SC cell is in the range of 2.1 V to 3 V. The capacity of single SCs ranges from hundreds of millifarads to a few kilofarads – they extend capacitor capacity range as the largest electrolytic capacitors are just around 1F incapacity. However, they have not replaced batteries due to relatively minuscule specific energy (7.4Wh/kg for 3400F capacitor), which makes them inappropriate for bulk energy storage. SC technology is evolving to improve the overall performance. Hybrid capacitors have been developed – they use both SC and Li-ion technology. The result is a so-called lithium-ion capacitor – as the name suggests, it is more like a capacitor with some features of the Li-ion battery.

To conclude this chapter, see the figure below – a Ragone plot, which is an effective tool to graphically compare gravimetric energy density (specific energy) and gravimetric power density (specific power) of various energy storage elements. The lowest performance is at the bottom left corner while the highest performance is at the top right corner - a spot to be taken by future technologies. As can be seen, fuel cell technology can provide the highest specific energy while capacitors can provide the highest specific power. However, Li-ion technology with its high specific energy and good specific power is the right choice for most mobile/portable applications.

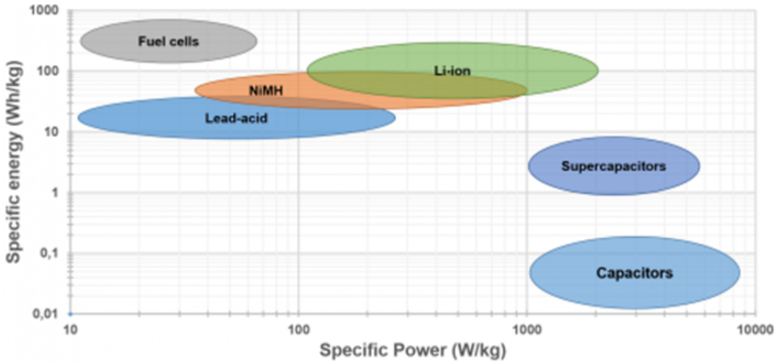


Figure 28. General Ragone plot of energy storage elements.

1.13. Electric motors

This chapter provides a very basic overview of the operational principles of electric motors.

The operation of any electric motor (machine) is based on the phenomenon of electromagnetic induction – the interaction of a conductor with an electric current and magnetic field. There are three fundamental concepts of implementation of an electric motor:

A permanent magnet (or electromagnet) motor

The current in the conductor influences the flux induced by a permanent magnet (or electromagnet) or opposite transformation.

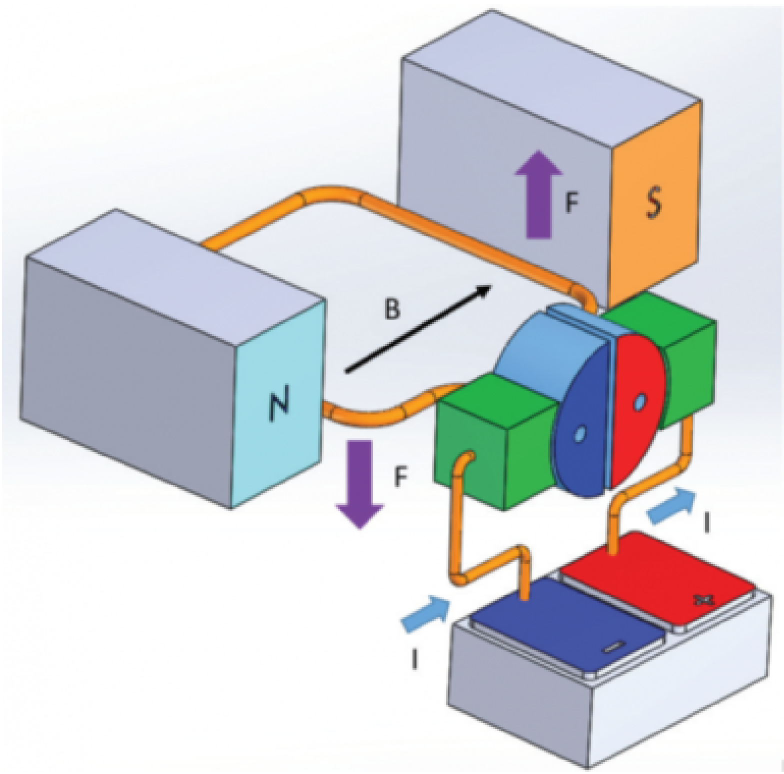


Figure 29. Schematic representation of an electric motor

In the figure:

```
I – The direction of the flowing current;
B – Direction of magnetic flux created by the permanent magnets
F – Force and its direction created by current and magnetic flux
In green – rotating contact surface enabling to change the direction of current
           while the motor is rotating.
In orange – conductor (a copper wire)
```

The created force creates momentum on the conductor i.e. it starts to rotate. During rotation the conductor changes the connection to the contact surfaces, thus changing the current direction in the conductor. The created momentum keeps turning the conductor and motor keeps running.

A rigid body motor

The current of the conductor influences a secondary magnetic flux induced by an electric current.

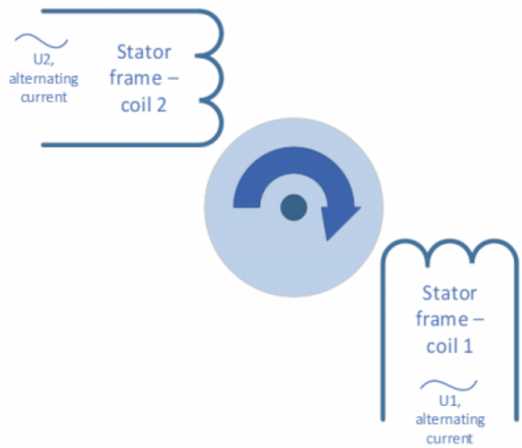


Figure 30. Schematic representation of a rigid body motor

In this case, a force on the rotating rigid magnetic body is created by two stator coils, where the flowing currents U1 and U2 differ in their phase i.e. the force is created by the phase shift.

Magnetic flux motor or Brushless motor

The magnetic flux induced by the current influences a ferromagnetic body (so-called reluctance principle). This type of motors is widely known as brushless direct current motors and widely used in different autonomous systems like drones due to the ability to provide a high output power relative to its size.

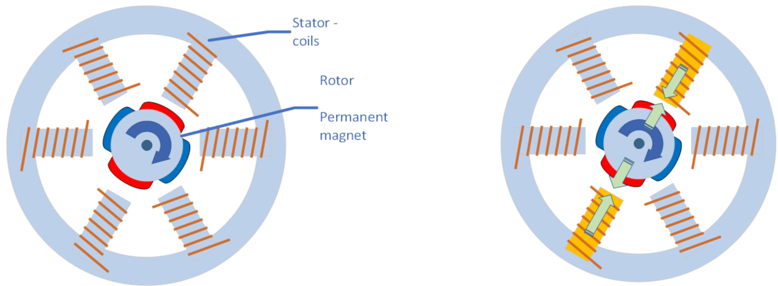


Figure 31. Schematic representation of brushless motor

The motor consists of a stator – coils and robots – permanent magnets (or single multi-pole magnet). If a direct current is applied to the pair of opposite coils a force and appropriate momentum is created on the magnets (figure on the left). If a control circuit keeps switching one pair of coils after another, the rotor will keep rotating due to sequentially generated force and momentum.

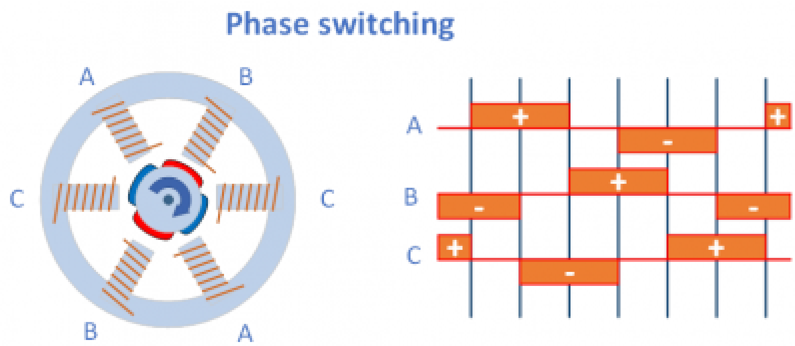


Figure 32. Phase switching schema

In all cases, a dedicated motor controller is used to ensure proper application of voltage and current to the motor. Other types of motors are derived from the mentioned ones.

2. Self-driving Vehicles Simulation

Autonomous vehicle (AV) development is one of the top trends in the automotive industry and the technology behind them has been evolving to make them safer. In this way, engineers are facing new challenges especially moving toward the Society of Automotive Engineers (SAE) levels 4 and 5. To put self-driving vehicles on roads and evaluate the reliability of their technologies they have to be driven billions of miles, which takes a long time to achieve unless with the help of simulation. Furthermore, due to the past real crash cases of AVs, a high-fidelity simulator has become an efficient and alternative approach to provide different testing scenarios for control of these vehicles, also enabling safety validation before real road driving. Different high-resolution virtual environments can be developed based on the real world for simulators by using cameras or lidars to simulate the scenarios as close as possible to the real. Also, virtual environment development enables us to customize and create various urban backgrounds for testing the vehicle. Creating a virtual copy of an existing intelligent system is a common approach nowadays called a digital twin.

2.1. Simulator

Simulation has been widely used in vehicle manufacturing, particularly for mechanical behavior and dynamical analysis. However, AVs need more than that due to their nature. Simulation in various complex environments and scenarios included other road users with different sensors combination and configuration enables us to verify their decision-making algorithms. One of the most popular robotic simulator platforms is Gazebo. It is based on ROS (Robot Operating System) and utilizes physics engines and various sensor modules suitable for autonomous systems. However, there are several modern AV simulators based on powerful game engines that enable us to simulate the scene as real as possible for having high-fidelity simulations. Simulators such as SVL or CARLA are the most popular ones that are used nowadays for simulating different scenarios.

2.2. Virtual Environment

Nowadays the fierce competition in the gaming industry has brought many features to the table in terms of game engines. These engines can simulate physics and thus can be exploited as simulators aside from game development. SVL and others have already taken advantage of these engines and have created a framework for testing autonomous vehicles within these physics simulators. However, even though these simulators provide some basic tools and assets to get started, it is not enough. To make it more realistic, we need real-life terrains simulated.

2.2.1. Data Collection and Processing

The first step of the Terrain generation is data collection of the desired area. Aerial imagery with a drone, over the area to be mapped, has to be conducted. The images are captured at a grid-based flight path. This ensures that the captured images contain different sides of a subject. In order to make sure the images have maximum coverage, the flight path is followed three times in different camera angles but at a constant altitude. All the images are georeferenced and IMU tagged to put the positioning and orientation data on them for better stiching and later processes. Then a dense point-cloud is created by using third-party software for the captured picture.

2.2.2. Terrain generation

Digitalization of a real-life environment can be used for simulating AVs in countless different scenarios without taking the vehicle out for once. Terrain generation from point-cloud is done right in Unity. The in-house developed plugin reads a pre-classified point-cloud file and based on chosen parameters it creates a normal map, a heightmap, and a color map to use in conjunction with the unity's terrain engine to create realistic environments.

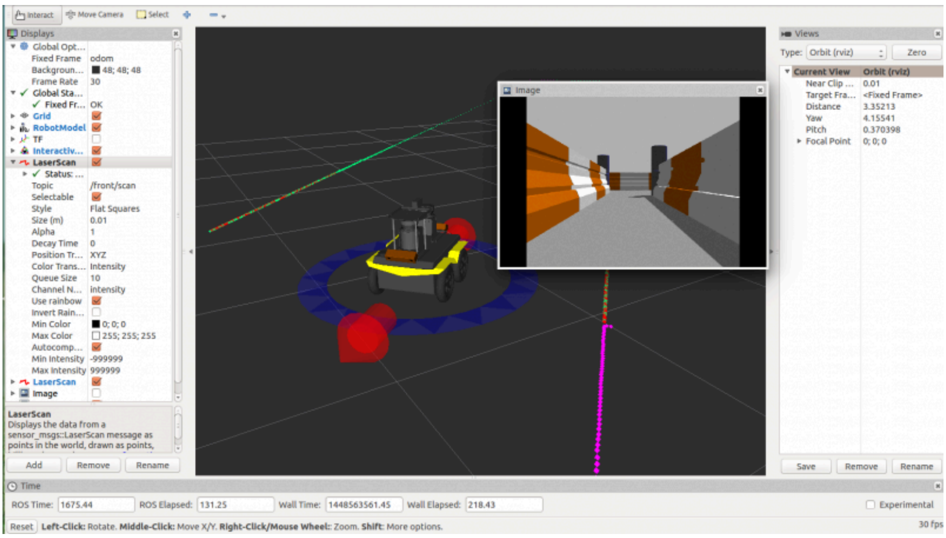
In the following, we have a brief introduction to AV basic requirements and simulation.

3. Robot Operating System

The Robot Operating System (ROS) is a flexible framework for writing robot software. It is a collection of tools, libraries, and conventions that aim to simplify the task of creating complex and robust robot behavior across a wide variety of robotic platforms. The below figure shows four different elements of ROS.

Plumbing: While multiple programs are running on your system, ROS enables these programs to communicate with each other. Also, it provides different device drivers to communicate easily with your hardware.

Tools: ROS has many basic tools which are important when you are working with robots such as, simulation, visualization, GUI, and data logging. These tools facilitate your efforts while you are working with robots.



Capabilities: There are several capabilities in ROS i.e. for control, planning, perception, mapping, manipulation and you can use what other experts already wrote for the ROS ecosystem. You don't need to create them from scratch.

Ecosystem: ROS is a big ecosystem. Software is organized in packages so you can easily install and use them. Ros provides the entire software distribution that includes many tutorials and documents that you can find online.

4. Installation and Configuration

There are many different versions of ROS. The latest version long term support(LTS) is currently ROS Noetic Ninjemys. For choosing the distribution or version you should consider your application. you can find useful information about choosing the right version in this page: http://wiki.ros.org/Distributions.

4.1. Installing ROS

Based on our application which is the autonomous vehicle we opt for ROS Melodic. Most versions of the packages work on this version, so this version is also used in this tutorial. ROS Melodic is primarily designed to run on the Ubuntu 18.04 LTS operating system. ROS can also be run in a separate Docker container. This allows ROS to run on many different operating systems and simplifies the management and development of robot software.

The development of ROS2 is already underway. You can read more about it at the official site: https://index.ros.org/doc/ros2/.

To make ROS easier to install on Ubuntu 18.04, an automated installation script has been created, which will run automatically to install all required packages. To run the installation script, use the following command on the terminal:

```
$ sudo apt update
$ sudo apt upgrade
$ wget https://raw.githubusercontent.com/ROBOTIS-GIT/robotis_tools/master/install_ros_melodic.sh
$ chmod 755 ./install_ros_melodic.sh
$ bash ./install_ros_melodic.sh''
```

4.2. Working Environment

One of the important working elements is the ROS working environment. It defines the context for the current workspace and you can also overlay different environments. Default workspace loaded with:

```
$ source /opt/ros/melodic/setup.bash
```

To create a new working environment; Create a folder named *catkin_ws*. If you used an automatic install script, you can skip creating a folder:

```
$ mkdir -p ~/catkin_ws/src # Create folders ~/catkin_ws/src
```

Compile *catkin* workspace:

```
$ cd ~/catkin_ws/ # Go to folder ~/catkin_ws/
$ catkin_make # compile the computing environment
```

command *catkin_make* is a handy tool for managing catkin workspaces. When you run this command, *CMakeLists.txt* is created and linked to the *src* folder. The *build* and *devel* folders are also created. Looking at the *devel* folder, you see that there are some *.sh files (*shell script*) in the folder:

```
$ ls -l devel
```

When extracting these files (*source*), the workspace variables are used. After that, packages in the workspace can be launched.

From the work environment you created earlier (catkin_ws) run this command:

```
$ source devel/setup.bash
```

To make sure that the *setup* script worked to check that the *ROS_PACKAGE_PATH* environment variable contains your workspace:

```
$ echo $ROS_PACKAGE_PATH
/home/youruser/catkin_ws/src:/opt/ros/melodic/share
```

Since multiple terminal windows are usually required to use ROS, and it would be tedious to use the workspace every time we add a *.baschrc* line that automatically takes our workspace when we open a new terminal window:

```
$ echo 'source ~/catkin_ws/devel/setup.bash' >> ~/.bashrc
```

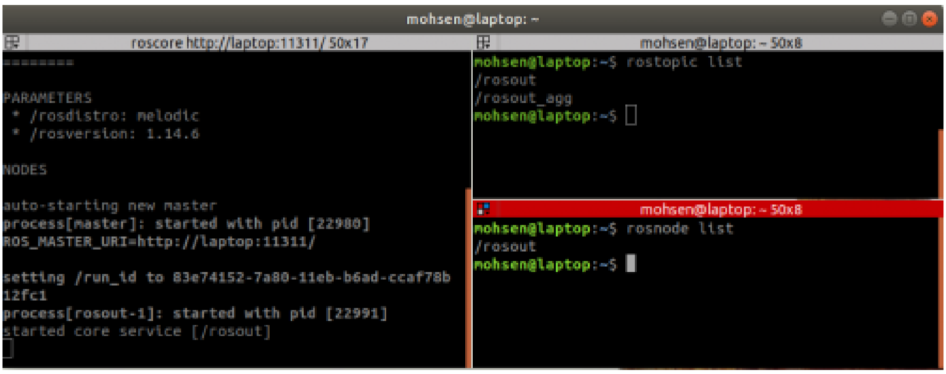
Your ROS environment is now configured and will be deployed automatically. Next, explore the ROS file system.

4.3. Useful Tools

There are a bunch of programming tools and software that really facilitate working with ROS and programming. Here we suggest Terminator as an alternative to the default ubuntu Terminal and Visual Studio Code as a good IDE (Integrated Development Environment).

4.3.1. Terminator

Terminator is an alternative terminal for Linux that comes with a few additional features and functionality that you won't find in the default terminal application. For instance, in Terminator you can split your terminal screen both horizontally and vertically as you wish. The user can also have multiple terminals in one window and use custom key bindings to switch between them.



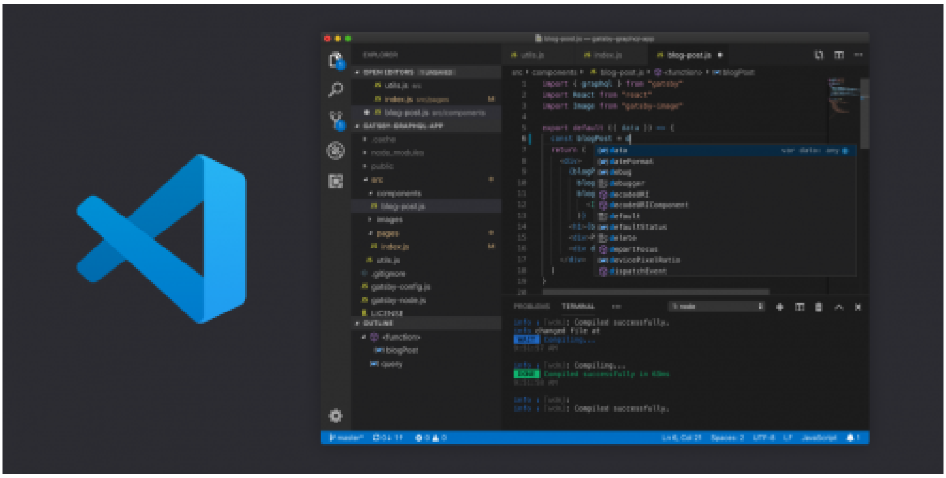
For installing the Terminator, run these commands in the terminal.

```
$ sudo add-apt-repository ppa:gnome-terminator
$ sudo apt-get update
$ sudo apt-get install terminator
```

Now you can open a new Terminal by "Ctrl + Alt + T" and for splitting the terminal screen right-click on the terminal and use split.

4.3.2. Visual Studio Code

Visual Studio Code is a freeware source-code editor made by Microsoft for Windows, Linux, and macOS. Features include support for debugging, syntax highlighting, intelligent code completion, snippets, code refactoring, and embedded Git.



For installing the VSCode you can follow the instruction in the Doc page:

```
https://code.visualstudio.com/docs/setup/linux
```

4.4. ROS Packages

ROS has software for organized packages. The package may contain ROS nodes, data sets, configuration files, third-party software, or any other program needed to run the program. The purpose of libraries is to provide useful functions that can be easily used for different purposes.

The libraries can be installed using the Linux package manager *apt-get* or placed in the *src* directory of your workspace. The package called *ros-tutorials* contains packages that demonstrate the capabilities of ROS and are necessary to follow this tutorial.

Install the package named *ros-tutorials*:

```
$ sudo apt-get install ros-melodic-ros-tutorials
```

Once the package is successfully installed, the working environment must be recompiled:

```
$ catkin_make #compile the computing environment
```

4.5. ROS Master

ROS Master manages the communication between nodes. Every node registers at startup with the master. The *ros master* node must work. This node can be started with *roscore*.

Open a new terminal window (Ctrl + Alt + T) and launch *roscore*:

```
$ roscore
```

If everything is set up correctly, something should appear on the terminal:

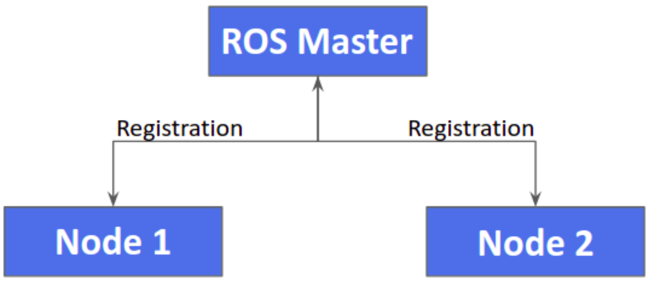
```
... logging to /home/mohsen/.ros/log/83e74152-7a80-11eb/roslaunch-laptop-22969.log
Checking log directory for disk usage. This may take a while.
Press Ctrl-C to interrupt
Done checking log file disk usage. Usage is <1GB.

started roslaunch server http://laptop:38393/
ros_comm version 1.14.6


SUMMARY
```

```
========

PARAMETERS
 * /rosdistro: melodic
 * /rosversion: 1.14.6

NODES

auto-starting new master
process[master]: started with pid [22980]
ROS_MASTER_URI=http://laptop:11311/

setting /run_id to 83e74152-7a80-11eb-b6ad-ccaf78b12fc1
process[rosout-1]: started with pid [22991]
started core service [/rosout]
```

Only one *roscore* can be run at a time. Now ROS nodes can communicate with each other.

4.6. ROS Nodes

ROS nodes are actually programs that run on your PC. It's a single-purpose and executable program that can be compiled, run, and managed individually. Nodes are like building blocks of your program. Nodes are organized in packages. Each package may include several nodes. Each node should be registered with the ROS master:



To run a node:

```
$ rosrun package_name node_name
```

To see the list of current active node:

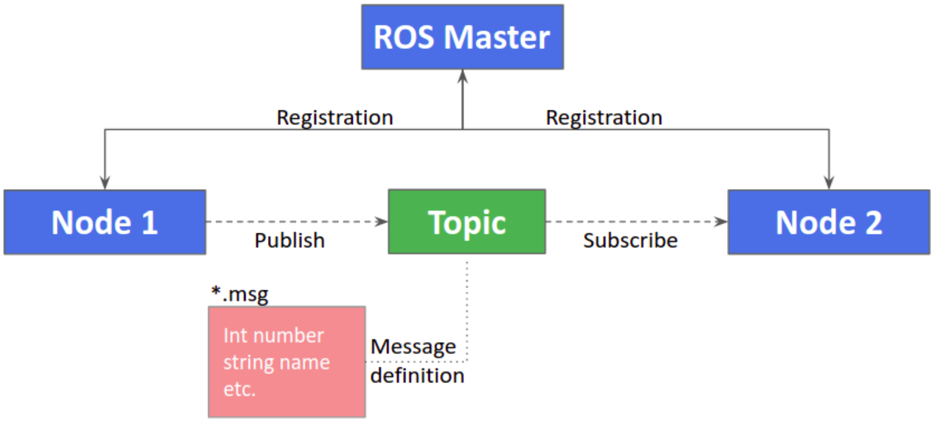
```
$ rosnode list
```

If you need to get some information about a specific node:

```
$ rosnode info node_name
```

4.7. ROS Topics

Nodes communicate with each other through ROS topics. One node can publish and subscribes to topics. Actually, topics are a stream of messages. The figure below shows how a topic transfer message between two nodes while one is publishing and the other is subscribing to the topic.



To see the list of active topics:

```
$ rostopic list
```

Subscribe and print the message inside a topic:

```
$ rostopic echo /topic_name
```

To get the information about a topic such as a publisher and subscribers and the type of the message:

```
$ rostopic info /topic_name
```

4.8. ROS Messages

Nodes publish messages over topics. Messages define the data structure of the information that flows from one node to the other. It includes simple data structures such as integers, floats, booleans, string, etc. They are defined in the *.msg file. You can see the message type inside a topic by running *rostopic info /topic_name*. To see the message structure of a specific type you need to run:

```
$ rosmsg show message_type
```

For example :

```
$ rosmsg show geometry_msgs/Twist
geometry_msgs/Vector3 linear
  float64 x
  float64 y
  float64 z
geometry_msgs/Vector3 angular
  float64 x
  float64 y
  float64 z
```

4.9. Sample Publisher and Subscriber

Above you installed a package called *ros-tutorials*. This package contains two nodes. The first node is called *talker*, which publishes the text "hello world" into the */chatter* topic.

We use *rosrun* to execute the node.

Open a new terminal window (Ctrl + Alt + T) and run a node called *talker* there:

```
$ rosrun rospy_tutorials talker
```

Make sure *roscore* is running, you can't start a node without it. If the node is successfully started, the terminal should appear:

```
[INFO] [WallTime: 1314931831.774057] hello world 1314931831.77
[INFO] [WallTime: 1314931832.775497] hello world 1314931832.77
[INFO] [WallTime: 1314931833.778937] hello world 1314931833.78
[INFO] [WallTime: 1314931834.782059] hello world 1314931834.78
[INFO] [WallTime: 1314931835.784853] hello world 1314931835.78
[INFO] [WallTime: 1314931836.788106] hello world 1314931836.79
```

The publisher goes and publishes messages to */chatter*, now you need a subscriber who listens to those messages.

The second node is called *listener* and subscribes to */chatter* and starts displaying messages sent to that topic.

Open a new terminal window (Ctrl + Alt + T) and execute a subscriber named *listener*:

```
$ rosrun rospy_tutorials listener
```

When messages sent by *talker* appear on the terminal, the node started successfully, ordered the */chatter*, and the nodes now communicate successfully through ROS:

```
[INFO] [WallTime: 1314931969.258941]/listener_17657_1314931968795I heard hello world
1314931969.26
[INFO] [WallTime: 1314931970.262246]/listener_17657_1314931968795I heard hello world
1314931970.26
[INFO] [WallTime: 1314931971.266348]/listener_17657_1314931968795I heard hello world
1314931971.26
[INFO] [WallTime: 1314931972.270429]/listener_17657_1314931968795I heard hello world
1314931972.27
[INFO] [WallTime: 1314931973.274382]/listener_17657_1314931968795I heard hello world
1314931973.27
[INFO] [WallTime: 1314931974.277694]/listener_17657_1314931968795I heard hello world
1314931974.28
[INFO] [WallTime: 1314931975.283708]/listener_17657_1314931968795I heard hello world
1314931975.28
```

ROS-based robots usually have a large number of nodes, each with its own specific function. Nodes can be located on different computers and communicate through different protocols. But now we're getting to know the tools that come with ROS, which allow us to track and manage nodes and topics.

4.9.1. Topics

Entering the *rostopic* command shows all the ways you can use it:

```
$rostopic
rostopic bw display bandwidth used by topic
rostopic echo print messages to screen
rostopic hz display publishing rate of topic
rostopic list print information about active topics
rostopic pub publish data to topic
rostopic type print topic type
```

Make sure roscore, talker and listener work in the background.

We will display all the topics currently in use:

```
$rostopic list
/chatter
```

```
/rosout
/rosout_agg
```

/chatter is the topic through which *talker* and *listener* interact.

We use the *rostopic info* command to display the necessary information about the topic:

```
$ rostopic info/chatter
Type: std_msgs/String

Publishers:
 * /talker_12621_1542817185271 (http://rage-HP-EliteBook:45495/)

Subscribers:
 * /listener_12836_1542817212996 (http://rage-HP-EliteBook:34711/)
```

You will see which nodes have subscribed to the topic and which ones are publishing to the topic, as well as the message type, which is *std_msgs/String*.

We use *rostopic hz* to see the frequency of messages:

```
$ rostopic hz/chatter
subscribed to [/chatter]
average rate: 10.005
min: 0.100s max: 0.100s std dev: 0.00017s window: 10
```

We see that the average frequency of messages is about 10 Hz (Ctrl + C aborts the process).

We use *echo* to display messages sent to the topic:

```
$ rostopic echo /chatter
date: "hello world 1542817743.91"
---
date: "hello world 1542817744.01"
---
date: "hello world 1542817744.11"
---
date: "hello world 1542817744.21"
---
date: "hello world 1542817744.31"
---
```

We use *pub* to post a message to:

```
$ rostopic pub /chatter std_msgs /String "data: 'hello world'"
publishing and latching messages. Press "Ctrl + C" to terminate
```

While listening to the subject at the same time, we see that the message we sent was published:

```
date: "hello world 1542817787.91"
---
date: "hello world 1542817788.01"
---
date: "hello world 1542817788.11"
---
data: "hello world"
---
date: "hello world 1542817788.21"
---
date: "hello world 1542817788.31"
---
date: "hello world 1542817788.41"
```

4.9.2. Nodes

We use *rosnode list* to display all currently running nodes.

```
$ rosnode list
/listener_12836_1542817212996
/rosout
/talker_12621_1542817185271
```

We use *rosnode info* to display the necessary information about the node:

```
$ rosnode info /talker_12621_1542817185271
-------------------------------------------------- ------------------------------
Node [/talker_12621_1542817185271]
Publications:
 * /chatter [std_msgs /String]
 * /rosout [rosgraph_msgs /Log]

Subscriptions: None

Services:
  * /talker_12621_1542817185271/get_loggers
 * /talker_12621_1542817185271/set_logger_level


contacting node http://rage-HP-EliteBook:45495/...
Hold: 12,621
Connections:
 * topic: /chatter
    * to: /listener_12836_1542817212996
    * direction: outbound
    * transport: TCPROS
 * topic: /rosout
    * to: /rosout
    * direction: outbound
    * transport: TCPROS
```

We can see which computer the node is running on and through which protocol it is connected to the ROS.

5. ROS Tools

Using simulations is a good way to learn ROS without having to own a physical robot. In this chapter we just use a 2D simulation called Turtlesim. This tutorial will give you a good idea of what ROS tools can do for you. First, run *roscore*:

```
$ roscore
```

Run the launch file demo for Turtlesim:

```
$ roslaunch turtle_tf turtle_tf_demo.launch
```

When the launch file is running, a simulation with a graphical user interface opens.

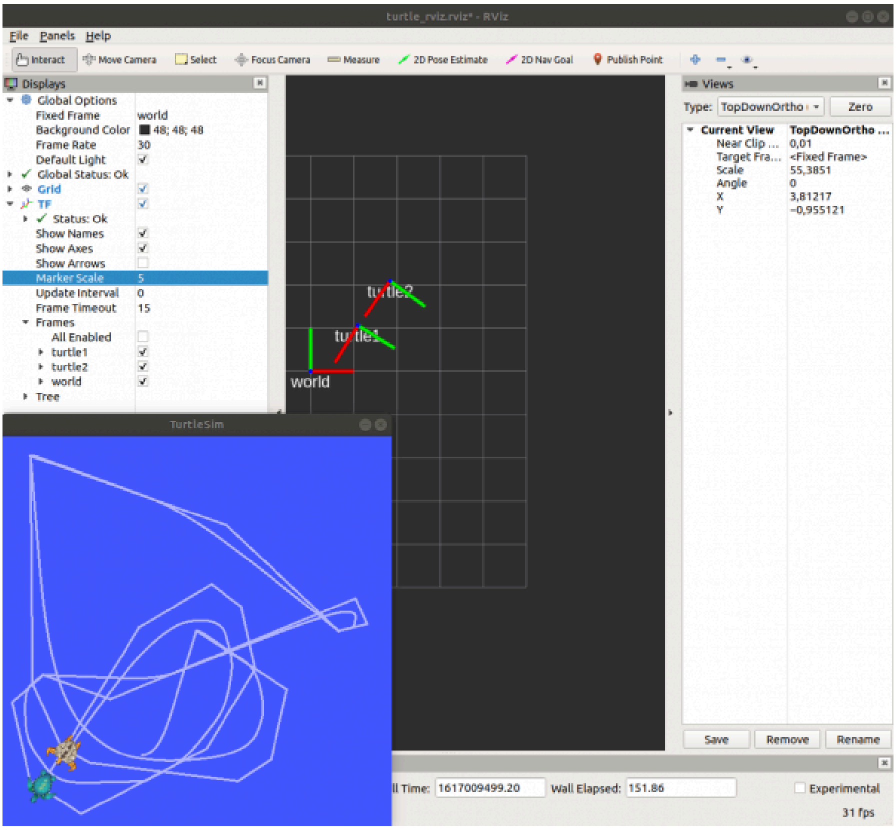
The launch file also contains a node that can be used to send keyboard movement messages to the robot. you need to click on the terminal that you opened the launch file and use arrow keys to move the turtlebot1. Then you can see that the second turtlebot will follow the first one.

5.1. RViz

Short for ROS Visualization. It’s a 3-dimensional visualization tool for ROS that helps to visualize what the robot seeing and doing. To run the RViz for the the turtlebot simulation there is a predefined configuration file that you can run it with the following command:

```
$ rosrun rviz rviz -d `rospack find turtle_tf`/rviz/turtle_rviz.rviz
```

As you can see there are three different transformation frame (tf) in the environment that each represents an element. The world is defined for the environment and turtle1 and turtle2 are for the robots. These transformation frames are useful for positioning and localization.



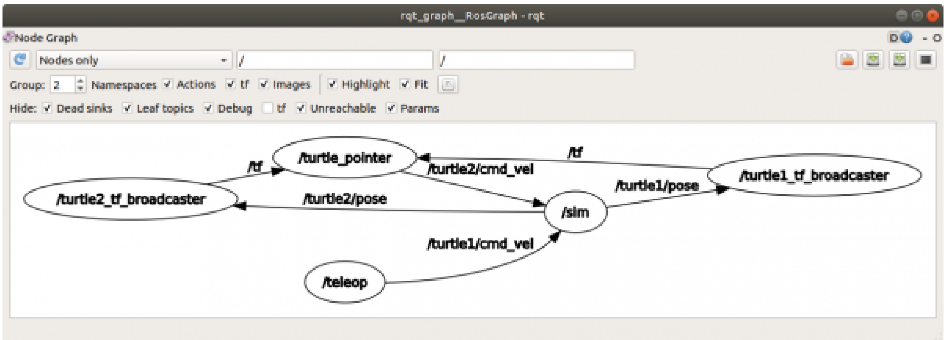
5.2. Rqt_graph

ROS also comes with some graphical tools. *Rqt_graph* graphically shows which nodes communicate with each other. It is also possible to filter nodes and topics differently. *rqt_graph* allows you to save the graph in *pdf* format.

run *rqt_graph*:

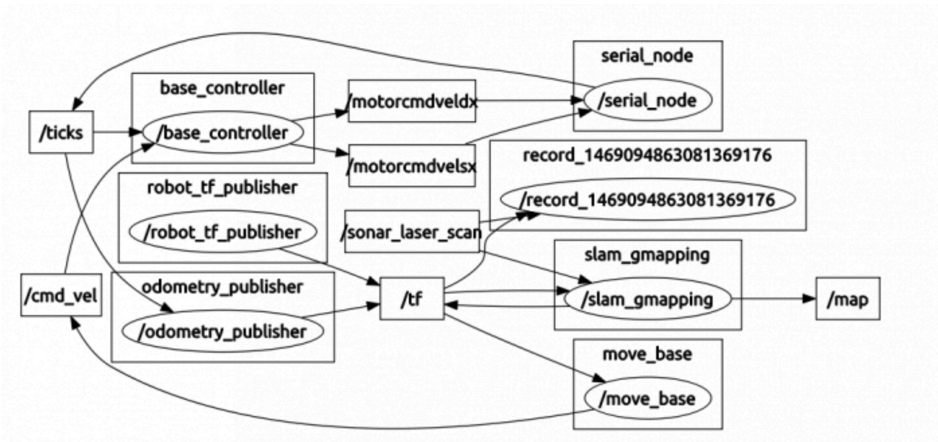
```
$ rqt_graph
```

When the command is executed, the graphical user interface opens. Robots with complex tasks usually have many different nodes working on them that interact with a variety of topics. It is difficult to see the big picture from the command line and this is done using the *rqt_graph* program. Let's see how it works using the *rqt_graph* tool, which visualizes the relationships between nodes and themes.



Launching the command opens a graphical user interface. We see that the */teleop* node reads the arrow keys and turns them into a robot motion. It is sent to */turtle1/cmd_vel*, which is listened to by a robot simulation. By running the same nodes on different computers, we can control the robot from another computer. A similar configuration is often used to control real robots. Also, there are two broadcasters for the TFs, */sim* node is publishing position in */turtl1/pose* and */turtle2/pose*.

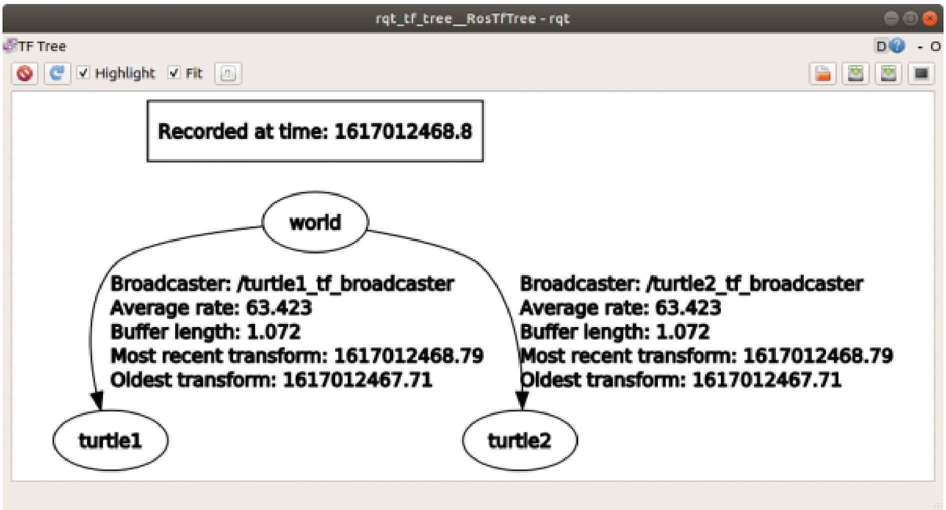
Example of a graph on a more complex robot:



5.3. Rqt_tf_tree

You can also use rqt tool to see the current transformation frames and relations. To see that run the following command:

```
$ rosrun rqt_tf_tree rqt_tf_tree
```

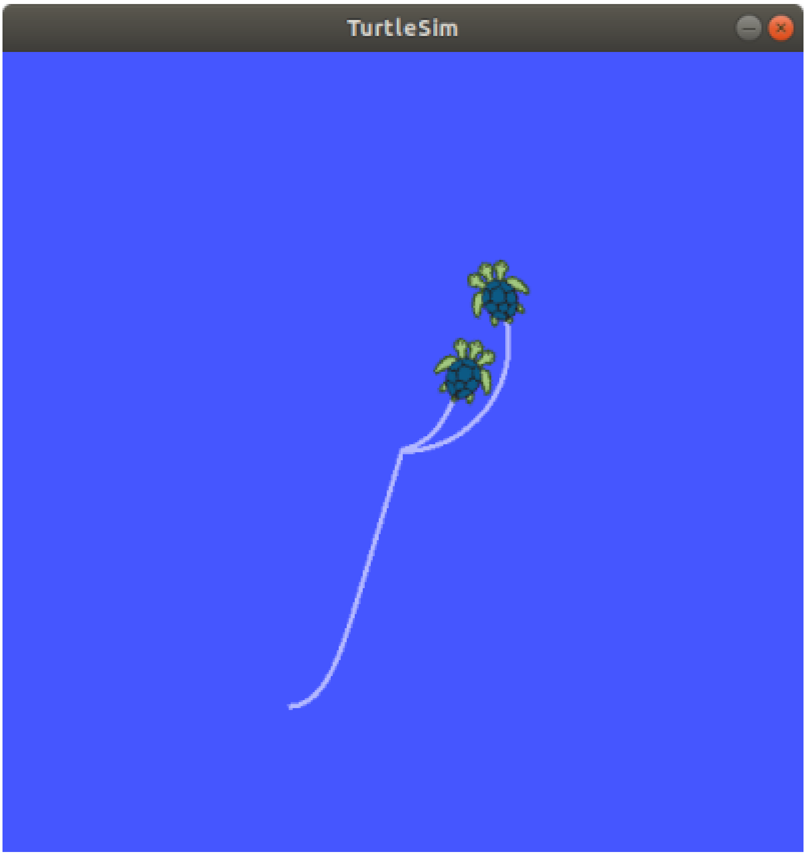


As can be seen in the GUI, two *turtle1* and *turtle2* frames are connected to the world tf. There are two broadcasters for them that calculate their transformation and publish them relative to the world.

5.4. Command line

The robot type is controlled by the message type *geometry_msgs/twist*, which consists of linear and angular velocities. Let's try to speed ourselves from the command line. The *TAB* key can be used to automatically complete the command. We use the *rostopic pub* tool *argument to r 1*, which sends the given message at 1 Hz:

```
 $ rostopic pub /turtle1/cmd_vel geometry_msgs/Twist "linear:
  x: 3.0
  y: 0.0
  z: 0.0
angular:
  x: 0.0
  y: 0.0
  z: 2.0"
```



We see that the robot moves from a circular motion in the simulation.

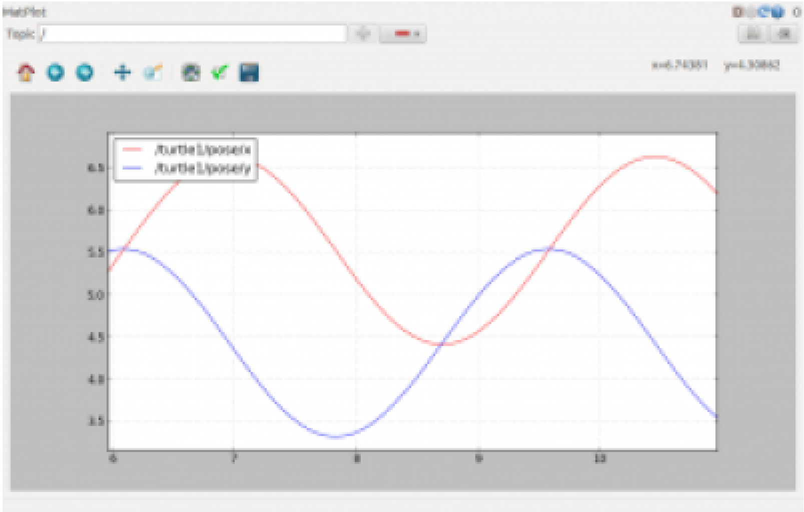
5.5. Rqt_plot

The *rqt_plot* tool is used to visualize the subject data over time. With this tool you can display the values of the messages as a graph. This tool can be used, for example, to visualize sensor values. Turtlesim simulator publishes the x and y coordinates of a robot in */turtle1/pose/x* and */turtle1/pose/y*. Let's try to display these topics on the graph.

Run *rqt_plot*:

```
$ rqt_plot
```

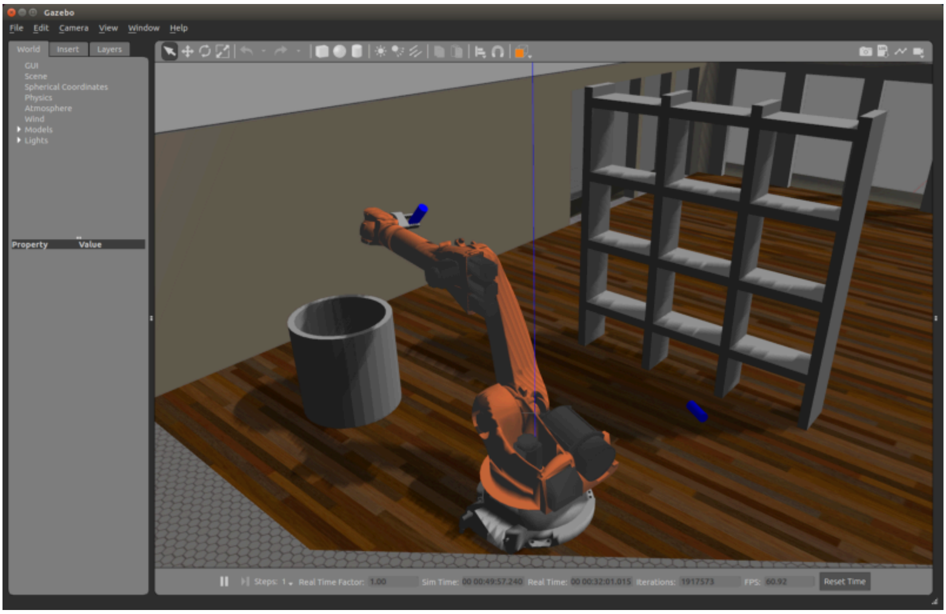
Adding */turtle1/pose/x* and */turtle1/pose/y* to the graph shows the real-time position of the robot on the x and y axes:


/turtle1/pose/x
/turtle1/pose/y

6. 3D Simulation

Simulation is the imitation of a real-world process or system over time. Previously, we dealt with simple two-dimensional simulations. Very sophisticated three-dimensional systems can also be simulated. Simulation is a very important part of the ROS and robot development process as it allows the robot to be programmed and experimented without having a physical robot. Robot simulation is an important tool for every robot builder. A well-developed simulator lets you quickly test algorithms, customize robots, and even train artificial intelligence. There are different types of simulators for various purposes. The Gazebo is a universal simulator for a wide variety of aims, from mobile robots to autonomous vehicles (AVs). However, AVs simulators need powerful graphical engines to create a virtual environment as close to the real one. This is beyond the Gazebo power and you can find this feature in the new modern AV simulator such as SVL simulator or CARLA.

In the first step, we chose Gazebo as the simulator and in the following focused on the SVL simulator as the main AV simulator. Gazebo offers the ability to accurately and efficiently simulate multiple robots in complex indoor and outdoor environments. The simulator has a full-featured physics engine, high-quality graphics, and good ROS compatibility. It is possible to simulate different motors and joints and different sensors, such as cameras and LiDARs. Gazebo simulator can be run from the command line (*headless*) or with a nice graphical user interface.



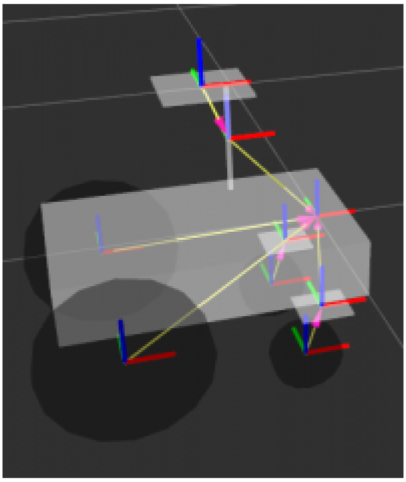
6.1. Installation

Gazebo is already installed with the full ROS installation. But in case that you don't install ROS in the full mode you can use this automatic installation script for installing Gazebo:

```
$ curl -sSL http://get.gazebosim.org|incl
```

6.2. URDF

The Unified Robot Description Format (URDF) is a robotic model in XML format. The model primarily contains the coordinates frames (*/tf*). These help us find out what the different parts of the robot depend on. For example, we find out where the robot is located on the camera. Basically, we can define static *tf* and also joints inside the URDF file. They are also used by simulators. According to this, the simulator knows the shape of the parts of the robot and where the joints of the robot are. Making URDF files may seem difficult at first, but fortunately, many popular robot models are freely available on the Internet.



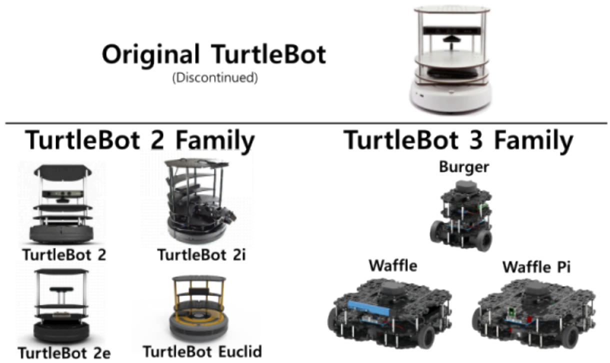
In order to modify the robot model both in the simulation and *in Rviz*, the robot's URDF file must be changed. This is necessary if we want to change the configuration of the robot, for example by adding sensors to the robot. Every element on the robot is assigned to a specific *link*. The relation between these links is defined under the *joint* tags.

Example URDF file:

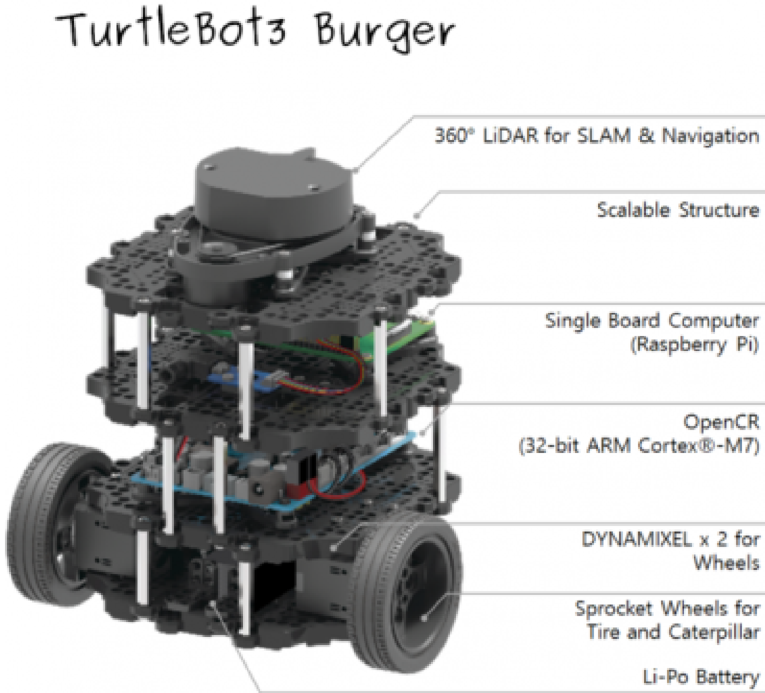
```
<? xml version = "1.0"?>
<robot name = "myRobot">
  <link name = "base_link">
    <visual>
      <geometry>
        <cylinder length = "0.6" radius = "0.2" />
      </geometry>
    </visual>
  </link>
  <link name = "right_leg">
    <visual>
      <geometry>
        <box size = "0.6 0.1 0.2" />
      </geometry>
    </visual>
  </link>
  <joint name = "base_to_right_leg" type = "fixed">
    <parent link = "base_link" />
    <child link = "right_leg" />
  </joint>
</robot>
```

7. Indoor Mobile Robot

TurtleBot is a flexible robotic platform designed to work with ROS. Built from common components, TurtleBot is modular and therefore allows the user to create many different configurations. Turtlebot is the ideal platform for experimenting with and learning about ROS. There are many users of the turntable, which means that many functions are freely available on the Internet in the form of ROS nodes. You don't have to write any lines of code to get Turtlebot to automatically navigate the space. All you need to do is find the right nodes on the Internet and get them working.

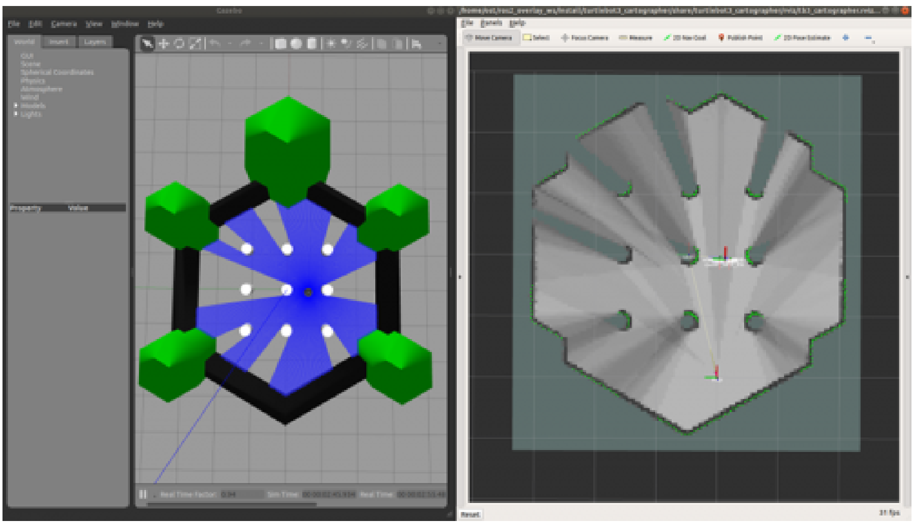


The most recent and developed version of the turtlebot is version 3. TurtleBot3 is made up of modular plates that users can customize shape. Available in three types: small-size Burger and medium-size Waffle, Waffle Pi. TurtleBot3 consists of a base, two Dynamixel motors, a 1,800mAh battery pack, a 360 degree LIDAR, a camera (+ RealSense camera for Waffle kit, + Raspberry Pi Camera for Waffle Pi kit), and SBC (single-board computer: Raspberry PI 3 and Intel Joule 570x) and a hardware mounting kit attaching everything together and adding future sensors. Turtlebot3 was released in May 2017.



7.1. Sensors

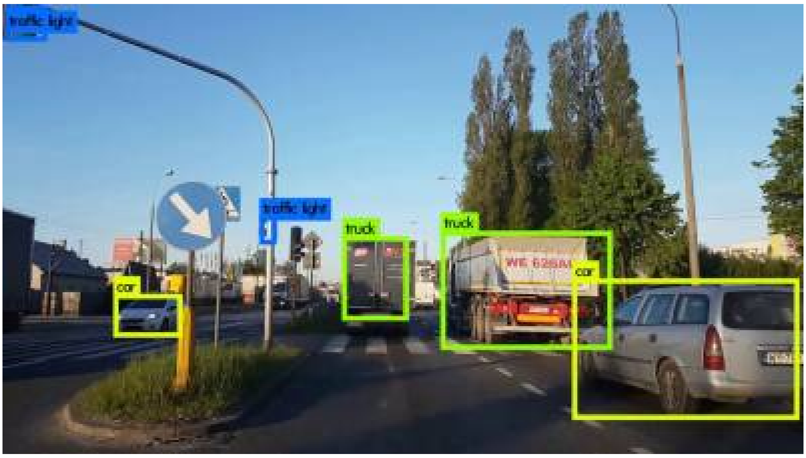
The main sensor of the turtlebot is the 360 Laser Distance Sensor LDS-01. The LDS-01 is a 2D laser scanner capable of sensing 360 degrees that collects a set of data around the robot to use for SLAM (Simultaneous Localization and Mapping). The below figure shows that how a robot sees the environment from a 360 laser sensor. The blue laser rays are reflected from the objects and the distance is measured and finally, a 2D point cloud of the environment is built.



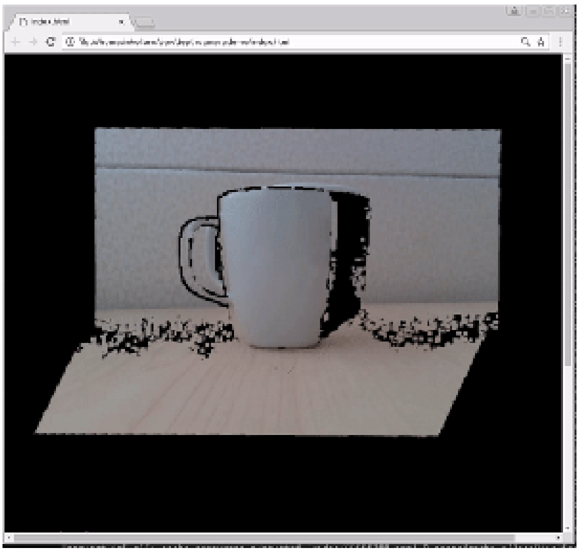
The 3D camera is one of the most versatile robot sensors. One output of a 3D camera is a 2D camera image, which means that various object recognition algorithms can be used. Many machine vision libraries are available for ROS. One of the most widely used and versatile is

OpenCV. In addition, for example, the most up-to-date artificial intelligence library You only look once (YOLO) is available.

Objects will be identified and a box will be drawn around them, with the name of the object type identified:



The advantage of a 3D camera over a conventional camera is the depth dimension. This allows the robot to sense the distance between objects. This feature allows the robot to develop autonomous navigation.



7.2. Turtlebot 3 Simulation

7.2.1. Install Dependent ROS 1 Packages

First of all, you need to install some dependencies. These are based on Ubuntu 18.04 and ROS Melodic.

```
$ sudo apt-get install ros-melodic-joy ros-melodic-teleop-twist-joy \
ros-melodic-teleop-twist-keyboard ros-melodic-laser-proc \
ros-melodic-rgbd-launch ros-melodic-depthimage-to-laserscan \
ros-melodic-rosserial-arduino ros-melodic-rosserial-python \
```

```
ros-melodic-rosserial-server ros-melodic-rosserial-client \
ros-melodic-rosserial-msgs ros-melodic-amcl ros-melodic-map-server \
ros-melodic-move-base ros-melodic-urdf ros-melodic-xacro \
ros-melodic-compressed-image-transport ros-melodic-rqt* \
ros-melodic-gmapping ros-melodic-navigation ros-melodic-interactive-markers
```

7.2.2. Install TurtleBot3 Packages

Install TurtleBot3 via Debian Packages.

```
$ sudo apt-get install ros-melodic-turtlebot3-msgs
$ sudo apt-get install ros-melodic-turtlebot3
$ sudo apt-get install ros-melodic-turtlebot3-gazebo
```

7.2.3. Install Simulation Package

The TurtleBot3 Simulation Package requires *turtlebot3* and *turtlebot3_msgs* packages as prerequisite. Without these prerequisite packages, the simulation cannot be launched.

```
$ cd ~/catkin_ws/src/
$ git clone -b melodic-devel https://github.com/ROBOTIS-GIT/turtlebot3_simulations.git
$ cd ~/catkin_ws && catkin_make
```

7.2.4. Set TurtleBot3 Model Name

Set the default *TURTLEBOT3_MODEL* name to your model. Enter the below command to a terminal.

In case of TurtleBot3 Burger:

```
$ echo "export TURTLEBOT3_MODEL=burger" >> ~/.bashrc
```

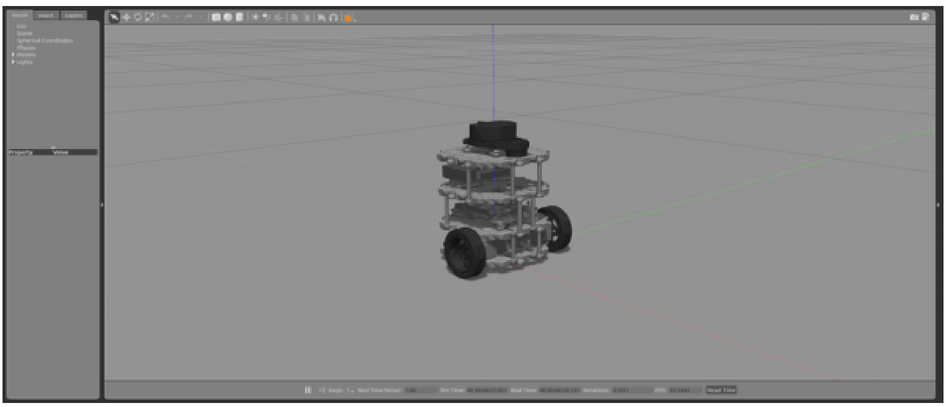
The above line write *export TURTLEBOT3_MODEL=burger* in *.bashrc* file in your home directory. So whenever you open a new terminal the "burger" is assigned to the *TURTLEBOT3_MODEL* variable.

7.2.5. Start the robot simulation

There are several predefined environments that you can run the turtle inside them. In the following, you can see an empty, sample and house world.

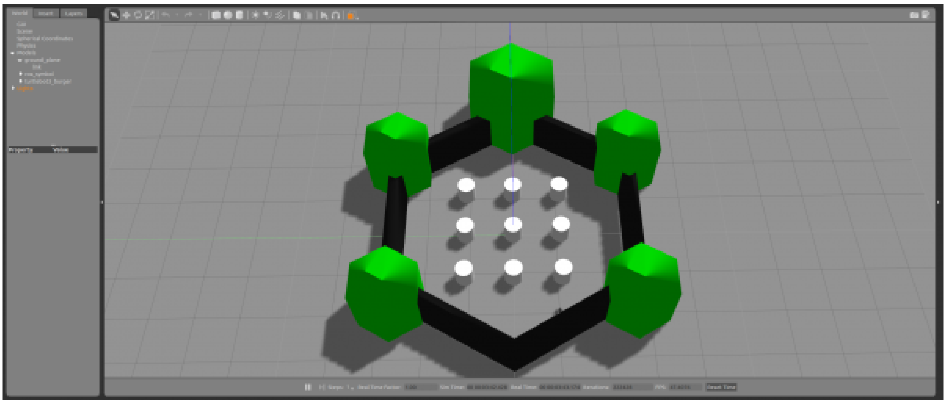
Empty World:

```
$ roslaunch turtlebot3_gazebo turtlebot3_empty_world.launch
```



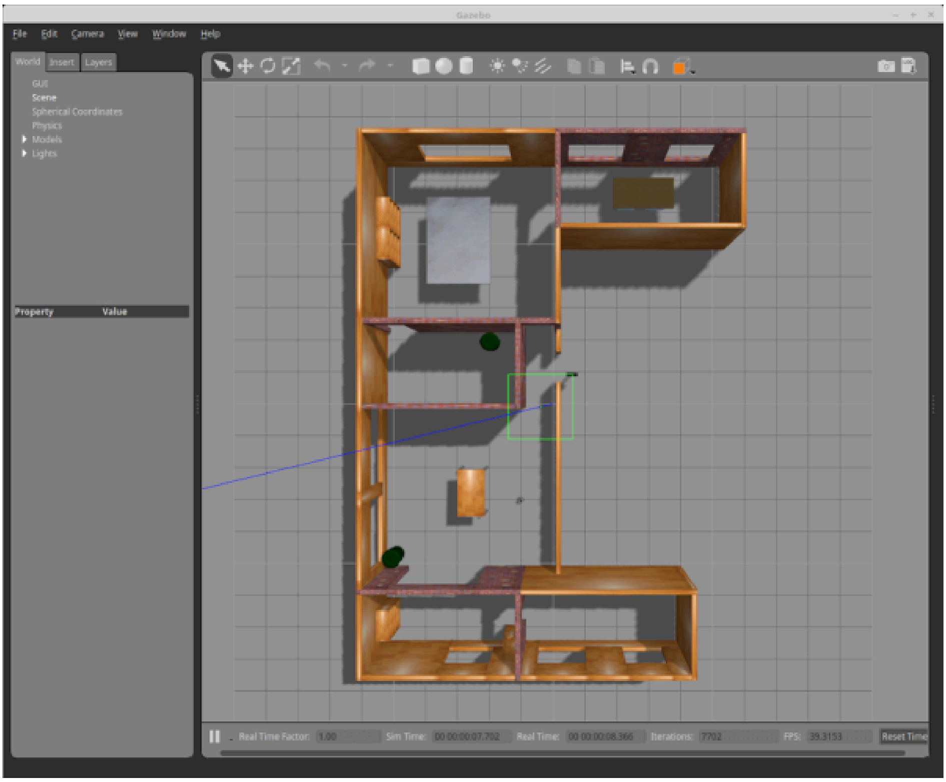
Sample World:

```
$ roslaunch turtlebot3_gazebo turtlebot3_world.launch
```

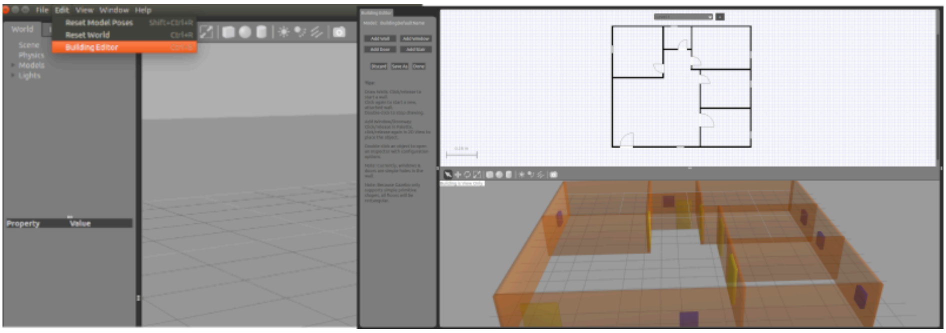


House:

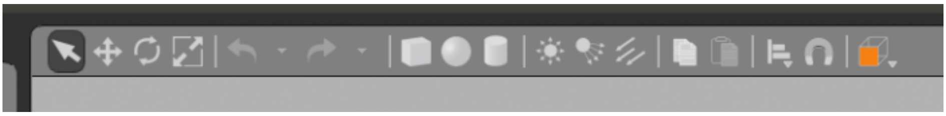
```
$ roslaunch turtlebot3_gazebo turtlebot3_house.launch
```



In case you need to build your environment, you can use Gazebo building editor tools (Edit > Building Editor) to create a customer shape building.



In the Gazebo Simulator, you can add simulation objects from the menu by clicking on the desired object. You'll also find tools for moving, enlarging, and rotating objects in the same place.



Next, we try to control the robot remotely.

7.2.6. Operate TurtleBot3

In order to teleoperate the TurtleBot3 with the keyboard, launch the teleoperation node with the below command in a new terminal window.

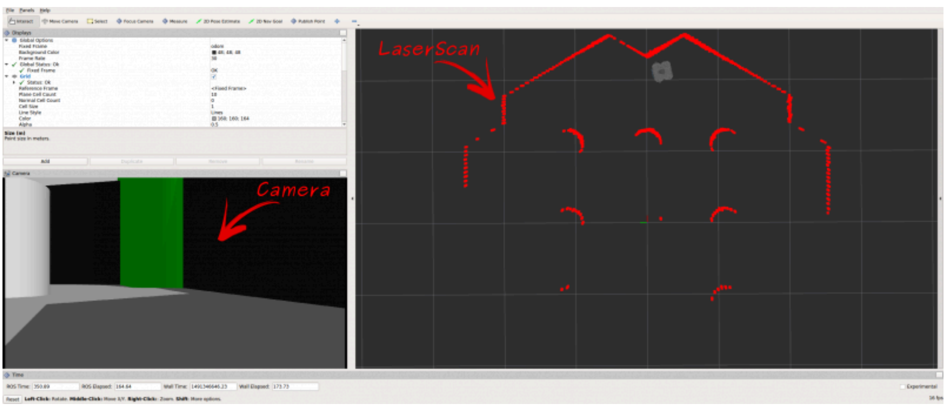
```
$ roslaunch turtlebot3_teleop turtlebot3_teleop_key.launch
```

Using the keyboard, we should now see how Turtlebot moves in the simulation.

7.3. Visualize Simulation data (RViz)

RViz visualizes published topics while the simulation is running. You can launch RViz in a new terminal window by entering the below command.

```
$ roslaunch turtlebot3_gazebo turtlebot3_gazebo_rviz.launch
```



7.3.1. SLAM Simulation

When SLAM (Simultaneous Localization and Mapping) in the Gazebo simulator, you can select or create various environments and robot models in the virtual world. We assume that you already launch the *turtlebot3_world.launch* file as shown above.

Run SLAM Node

Open a new terminal, and run the SLAM node. Gmapping SLAM method is used by default. We already set the robot model to burger in the *.bashrc* file.

```
$ roslaunch turtlebot3_slam turtlebot3_slam.launch slam_methods:=gmapping
```

Run Teleoperation Node

Open a new terminal with Ctrl + Alt + T and run the teleoperation node. Move the robot and take a look to RViz, you are scanning the area by the laser sensor and creating a map out of it.

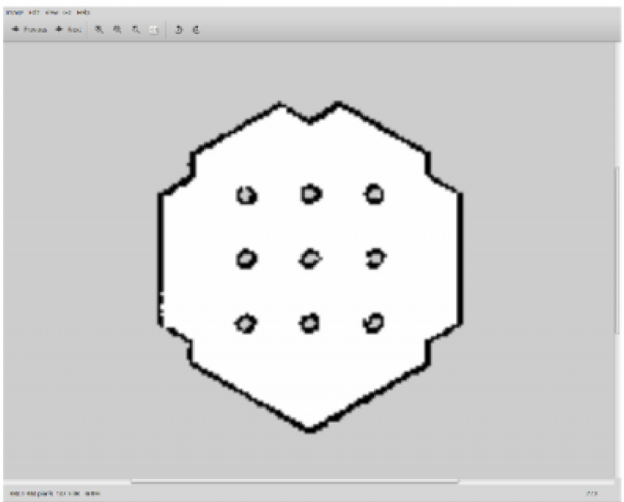
```
$ roslaunch turtlebot3_teleop turtlebot3_teleop_key.launch
```

```
Control Your TurtleBot3!
---------------------------
Moving around:
       w
  a    s    d
       x

w/x : increase/decrease linear velocity
a/d : increase/decrease angular velocity
space key, s : force stop

CTRL-C to quit
```

Save the Map

When the map is created successfully, open a new terminal from Remote PC with Ctrl + Alt + T and save the map.

```
$rosrun map_server map_saver -f ~/map
```



7.3.2. Navigation Simulation

Just like the SLAM in the Gazebo simulator, you can select or create various environments and robot models in a virtual Navigation world. However, a proper map has to be prepared before running the Navigation.

1) Launch Simulation World

Stop all previous launch files and running the node by "Ctrl + C". In the previous SLAM section, "TurtleBot3_World.world" is used to create a map. The same Gazebo environment will be used for Navigation. So run the simulation in the same world file :

```
$ roslaunch turtlebot3_gazebo turtlebot3_world.launch
```

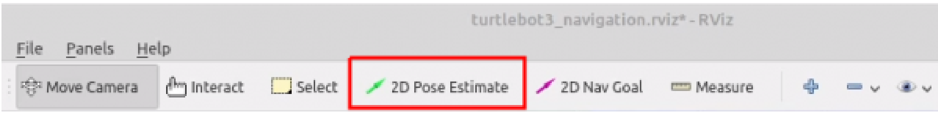
2) Run Navigation Node

```
$ roslaunch turtlebot3_navigation turtlebot3_navigation.launch map_file:=$HOME/map.yaml
```

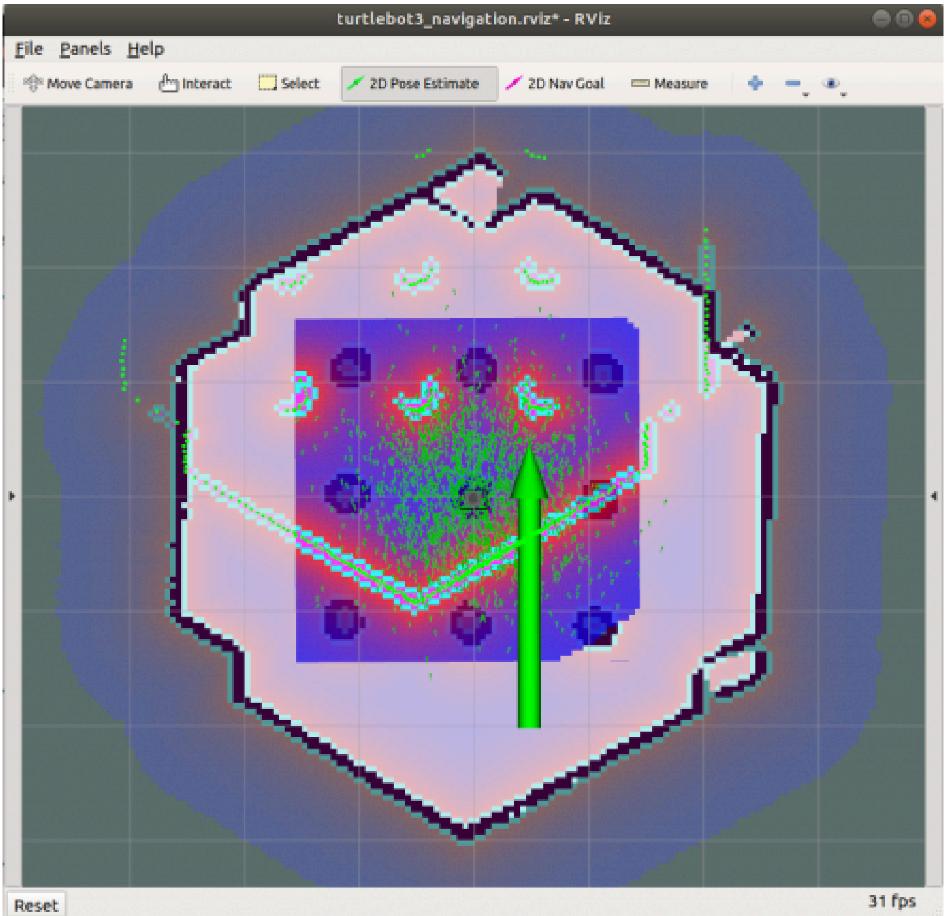
3) Estimate Initial Pose

Initial Pose Estimation must be performed before defining the destination for autonomous navigation as this process initializes the AMCL parameters that are critical in Navigation. TurtleBot3 has to be correctly located on the map with the LDS sensor data that neatly overlaps the displayed map.

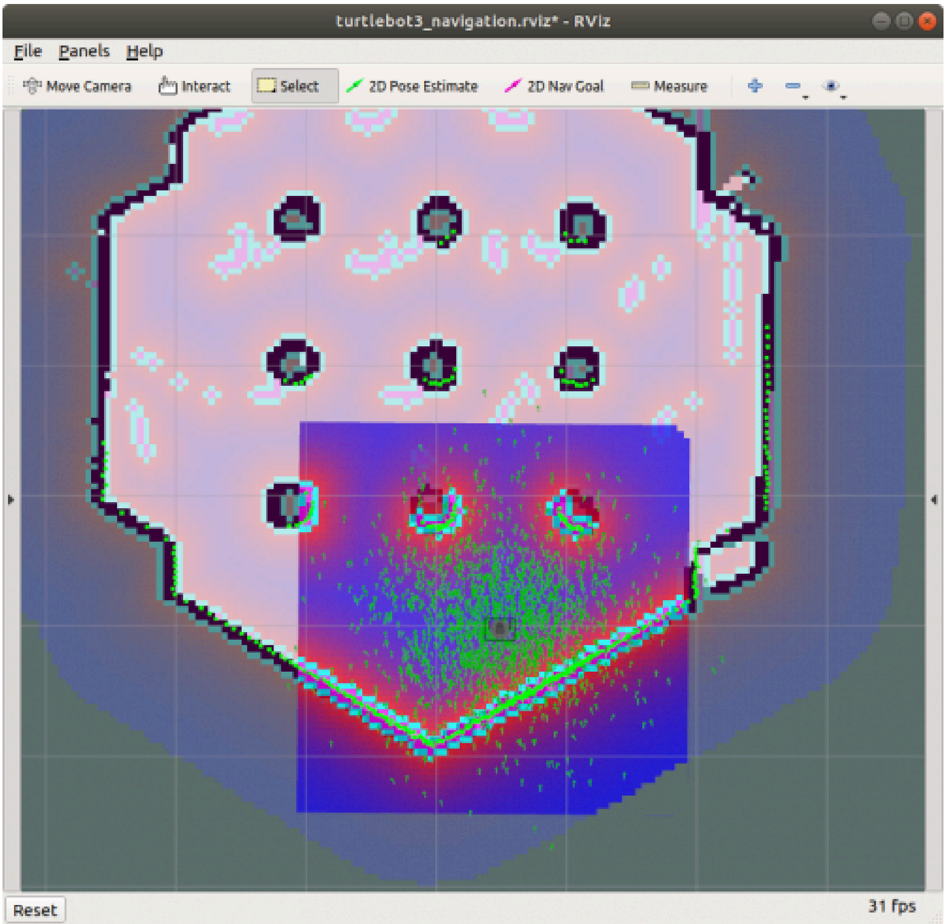
3.1) Click the 2D Pose Estimate button in the RViz menu.



3.2) Click on the map where the actual robot is located and drag the large green arrow toward the direction where the robot is facing.



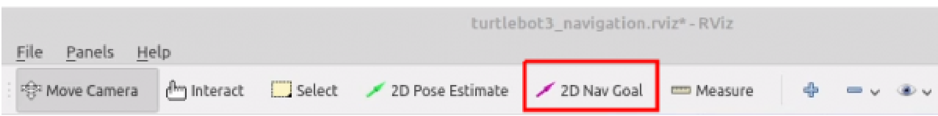
You can repeat steps 1) and 2) until the LDS sensor data is overlayed on the saved map.



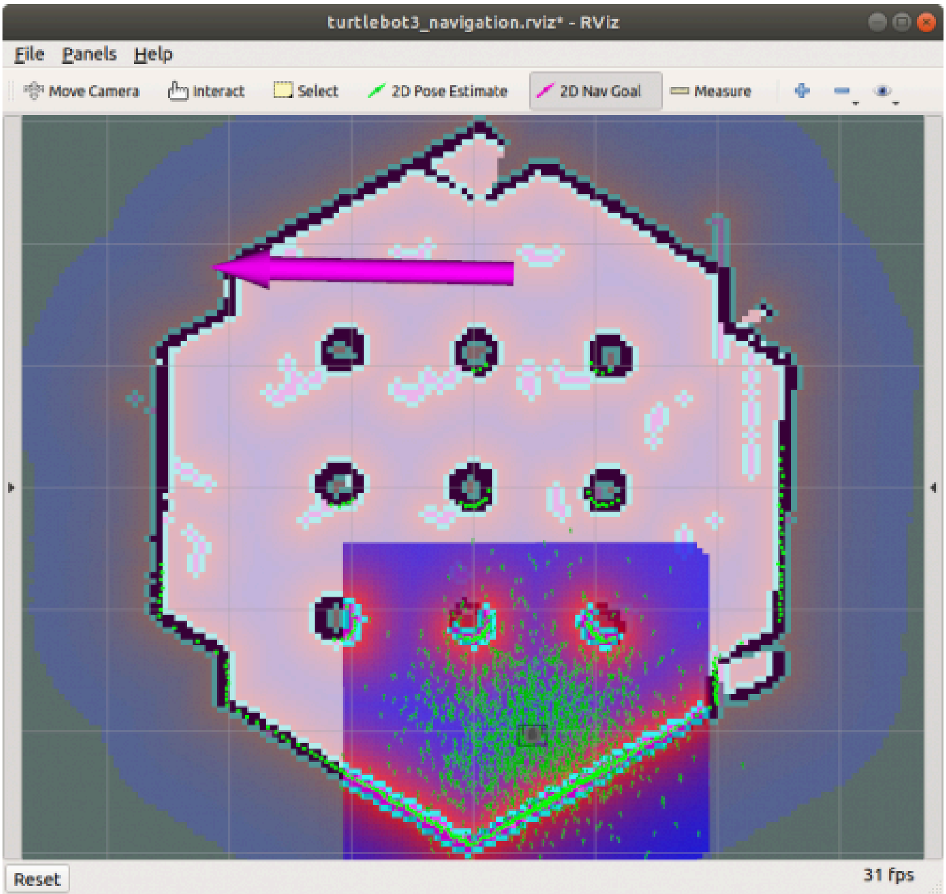
NB! 2D Pose Estimate actually publishes the position and direction into the /initialpose topic. So you can publish it by the command line or a script.

4) Set Navigation Goal

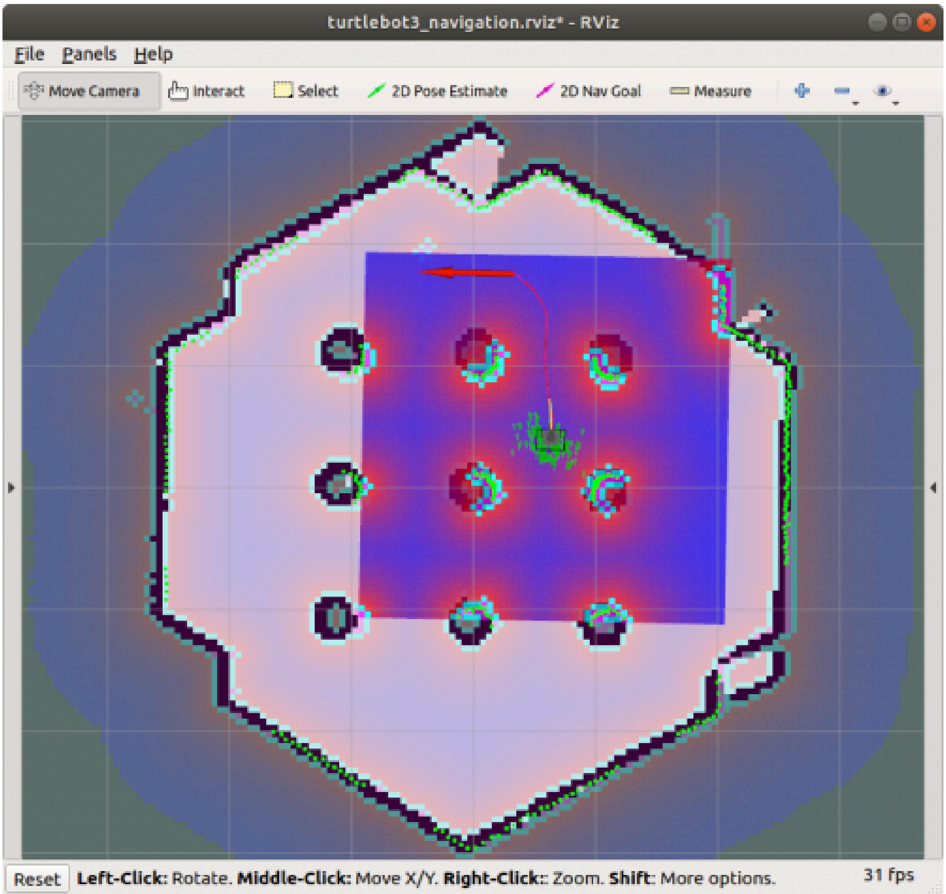
4.1) Click the 2D Nav Goal button in the RViz menu.



4.2) Click on the map to set the destination of the robot and drag the green arrow toward the direction where the robot will be facing.

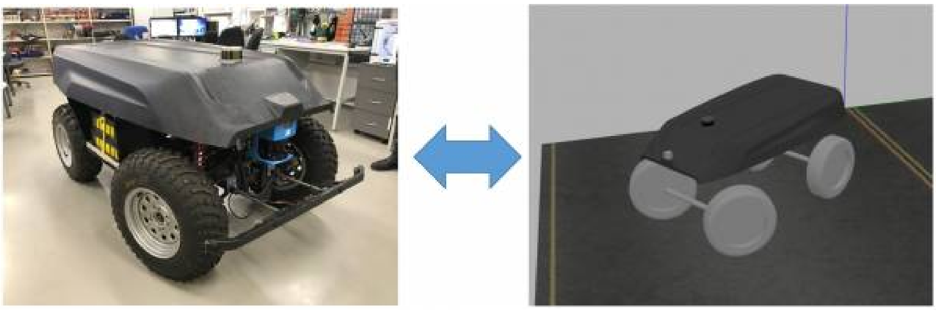


- This green arrow is a marker that can specify the destination of the robot.
- The root of the arrow is x, y coordinate of the destination, and the angle θ is determined by the orientation of the arrow.
- As soon as x, y, θ are set, TurtleBot3 will start moving to the destination immediately.


turtlebot3_navigation.rviz* - RViz
File Panels Help
Move Camera
Interact
Select
2D Pose Estimate
2D Nav Goal
Measure
Reset
Left-Click: Rotate. Middle-Click: Move X/Y. Right-Click:: Zoom. Shift: More options.
31 fps

8. Outdoor Mobile Robot

Outdoor mobile robot UKU is a mid-sized self-driving vehicle for educational and research purposes. A Gazebo simulator model has been created to experiment with the UKU robot. This allows anyone, no matter where they are, to program the robot, and if the program runs correctly in the simulator, it can simply be run on a real robot.



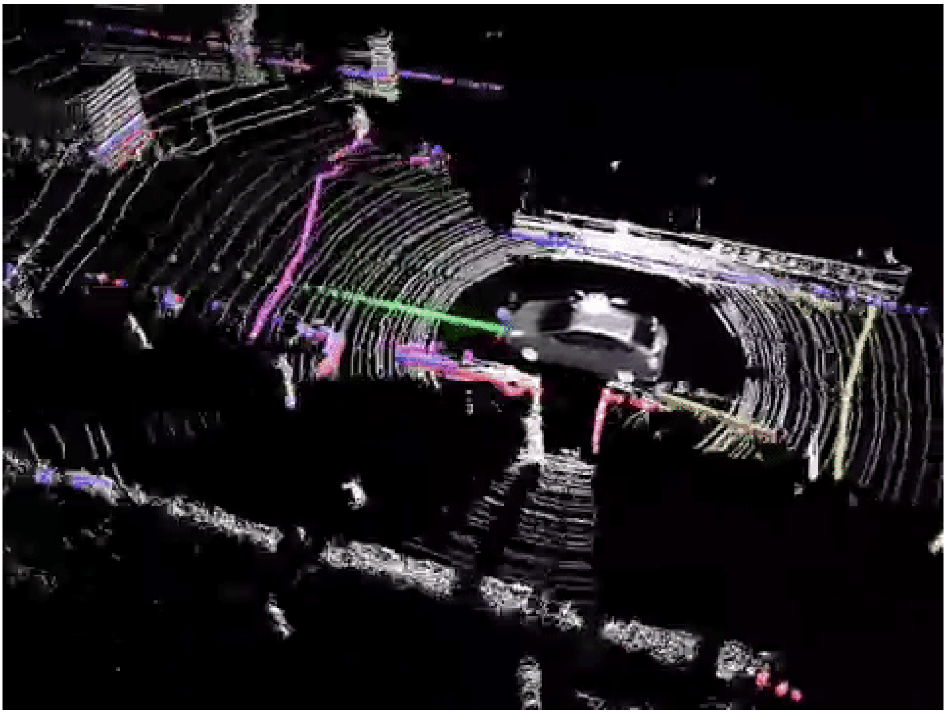
8.1. Sensors

LiDAR

The UKU's main sensor is Lidar. Lidars are very good sensors to sense the surroundings, but they are also relatively expensive. The use of capable lidars because of their price limits their use on personal robots. UKU uses a 3D Lidar *Velodyne VLP-16*. Lidar has 16 channels and 360 ° viewing angle. This means that Lidar emits 16 rays vertically in each direction. This Lidar is also used by most self-driving vehicles and other sophisticated self-driving robot systems.

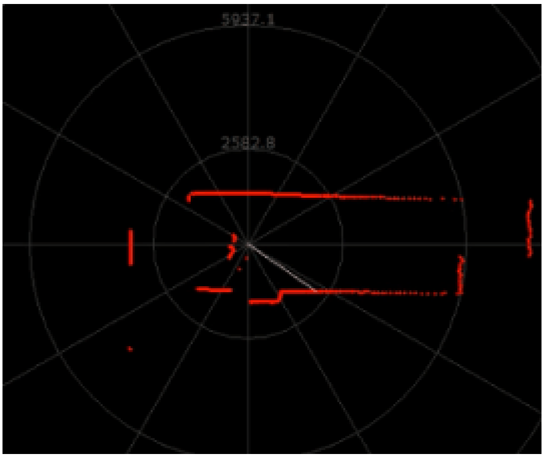
<table>
<tr><th colspan="3">Velodyne VLP-16 Specification</th></tr>
<tr><th>Spec.</th><th colspan="2">Value</th></tr>
<tr><td>Channels</td><td>16</td><td rowspan="7">
</td></tr>
<tr><td>Measurement Range</td><td>100 m</td></tr>
<tr><td>Range Accuracy</td><td>Up to ±3 cm (Typical)</td></tr>
<tr><td>Field of View (Vertical)</td><td>+15.0° to -15.0° (30°)</td></tr>
<tr><td>Angular Resolution (Vertical)</td><td>2.0°</td></tr>
<tr><td>Angular Resolution (Horizontal/ Azimuth)</td><td>0.1° – 0.4°</td></tr>
<tr><td>Rotation Rate</td><td>5 Hz – 20 Hz</td></tr>
</table>

Lidar allows laser beams to obtain a point cloud from the surroundings, which is very useful for autonomous navigation. The more channels the Lidar has and the higher its resolution, the more accurate the point cloud will be.



The *Velodyne VLP-16* Lidar on top of the UKU robot is expensive and simpler and cheaper Lidars can also be used in simpler applications. One of the most popular cheaper Lidar is RPlidar. *RPlidar A1* costs around 100 € and *RPlidar A3* 600 €. Lidars differ mainly in the resolution and measurement frequency.

RPlidar has a 360° field of view but has only one channel. Therefore, the output of the Lidar is two-dimensional. Such Lidars are a good choice for navigating indoors where walls and other vertical objects are obstructed.



In the Gazebo simulator, it is also possible to simulate Lidars. Many Lidar manufacturers have published Lidar models (URDF) on the Internet, which makes adding a Lidar to their robot model much easier. The official *Velodyne VLP-16* URDF model is also used in the UKU robot simulation.

8.2. UKU Simulation

The necessary models and libraries for experimenting with the robot have been created to simulate the robot in Gazebo. For convenience, the entire ROS workspace has been uploaded to a git repository. Simply download the working environment and install the necessary libraries to use the simulation.

Let's start by cloning the repository:

```
$ sudo apt install git
$ git clone http://gitlab.robolabor.ee/ingmar05/uku_simulation_ws.git
```

Install the required libraries and compile:

```
$ cd uku_simulation_ws
$ rosdep install --from-paths src --ignore-src -r -y
$ catkin_make
$ source devel / setup.bash
```

So that we don't have to get a working environment every time we open a new terminal window, we can add the following line to the *.bashrc* file:

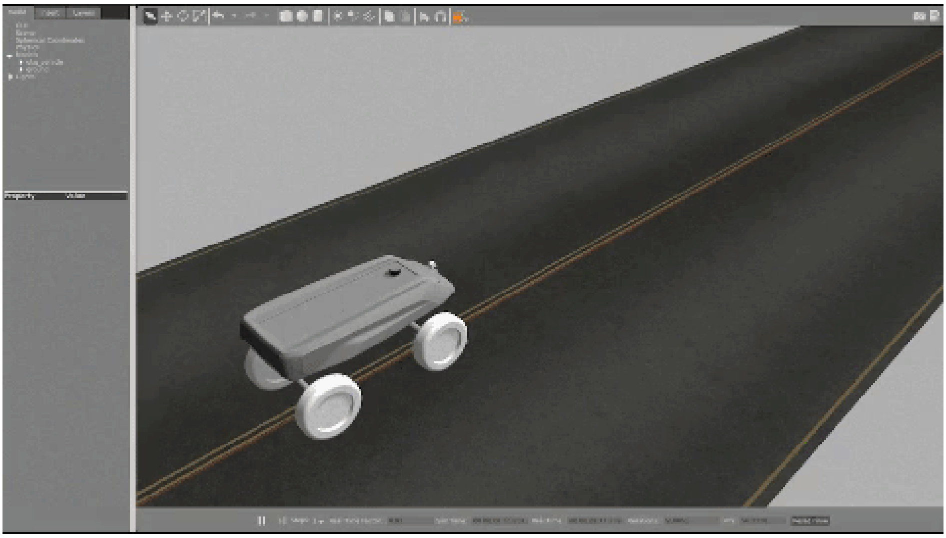
```
$ echo "source ~/uku_simulation_ws/devel/setup.bash" >> ~/.bashrc
```

To avoid having to manually launch multiple nodes each time with the correct parameters, launch files (*.launch*) have been created. Using these, you can execute *roscore* with one command and several different nodes with the correct parameters. To run all the necessary nodes to simulate the robot, a startup file called *uku_vehicle.launch* has been created.

Run simulation:

```
$ roslaunch uku_vehicle_gazebo uku_vehicle.launch
```

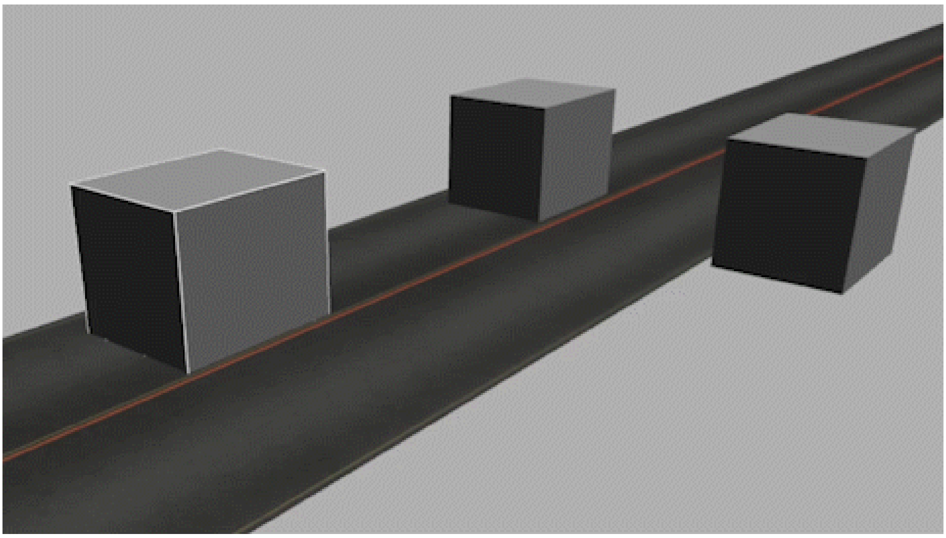
The Gazebo simulator and *Rviz* should now open. The UKU robot should be visible in the Gazebo virtual world. Using the *Gazebo* interface, we can add objects to the virtual world.



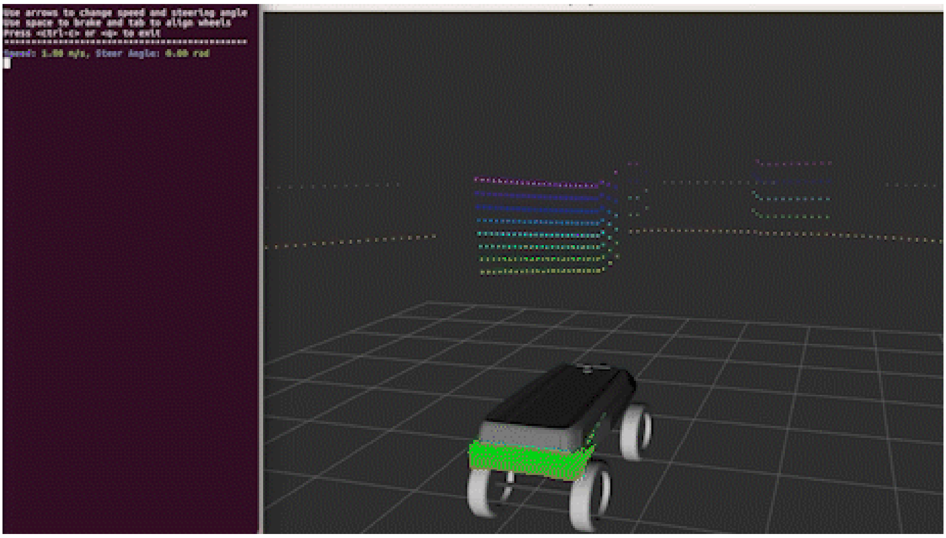
A robot remote control unit is also included with the workspace. Launch Remote Control Node in another window:

```
$ rosrun ackermann_drive_teleop keyop.py
```

Now we should be able to control the robot with the keyboard.



The startup file also launched the *Rviz* visualization tool. When we open the *Rviz* window, we see a 3D Lidar image and a robot model.


Use arrows to change speed and steering angle
Use space to brake and tab to align wheels
Press <ctrl-c> or <q> to exit

9. Self-driving Vehicle

Self-driving vehicles can fall into many different categories and levels of automation as described in previous chapters. One of the higher-level self-driving vehicles available nowadays is a Level 4 self-driving robot bus or Automated Vehicle (AV shuttle), also called a last-mile autonomous vehicle. The following describes an AV shuttle designed and developed in Tallinn University of Technology in cooperation with industrial partners in Estonia.

9.1. Vehicle Description

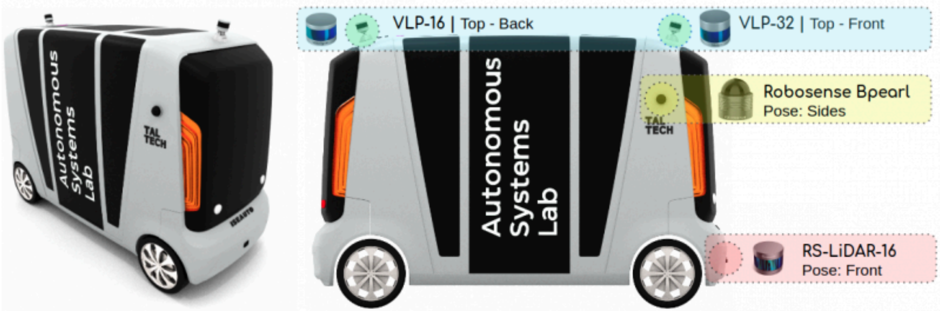
The iseAuto project was a cooperation project between industry and university which has a range of objectives from both sides as well as a very practical outcome. The project started in June 2017, when TalTech and Silberauto Estonia agreed to jointly develop a self-driving bus that had its public demonstration in September 2018. The purpose from the company's side was to get involved with self-driving technology to be aware of the future of the automotive industry and also get experience in manufacturing a special purpose car body, as that is one of the main activities of one of the branches of the company.

Vehicle specifications:

- Carriage of luggage or persons for 4 + 2 persons
- Average driving speed is 10–20 km/h
- Turning radius 9 m
- Main engine power 47 kW
- Battery pack 16 kWh

Sensors:

- Front-top LiDAR Velodyne VLP-32
- Back-top LiDAR Velodyne VLP-16
- Side LiDAR Robotsense Bpearl x 2
- Front-bottom LiDAR Robosence 16
- Cameras
- RTK-GNSS
- IMU



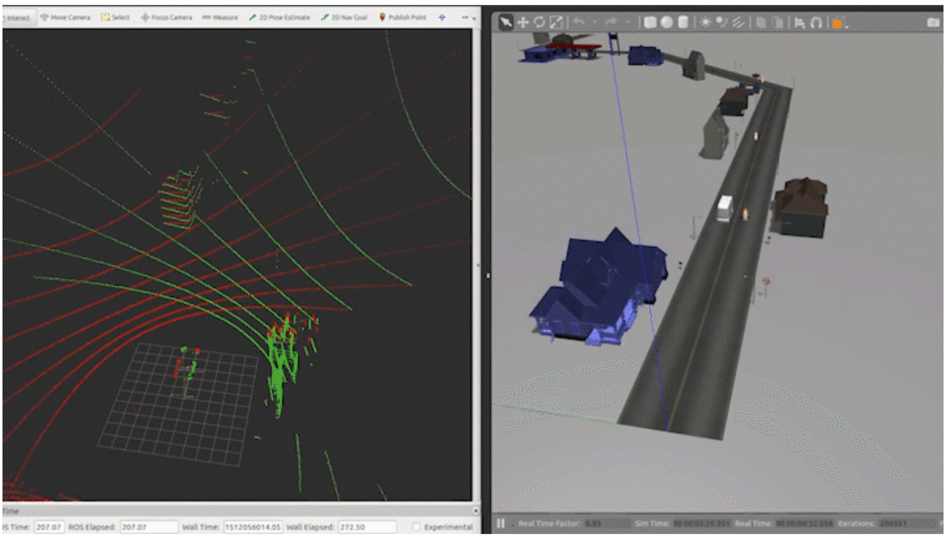
The iseAuto 3D model and its Lidar sensors are illustrated in the above figure. Two Velodyne VLP-16 and VLP-32 are installed at the top back and front of the vehicle respectively. Furthermore, two Robosense Bpearl are installed at the sides left and right of the vehicle. Finally, one Robosence LiDAR-16 is installed at the front bottom of the vehicle to cover the front blind zone. This Lidar configuration can create a good point cloud coverage around the vehicle for perception purposes.

Software:

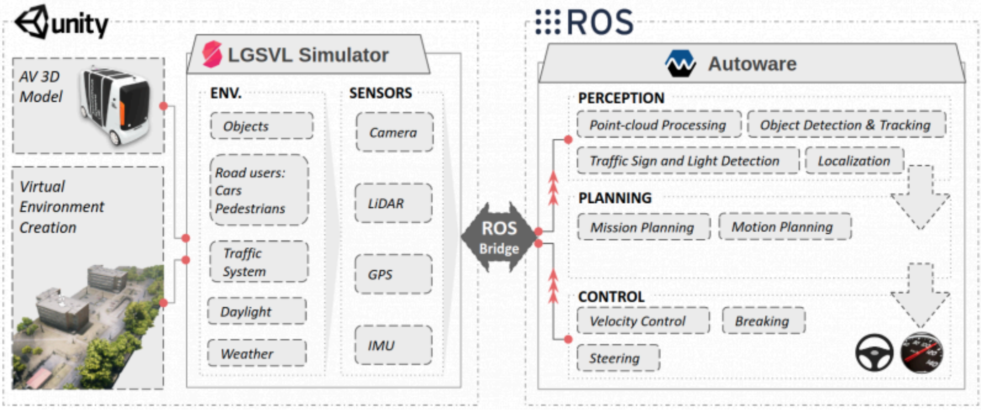
- Robot Operating System (ROS);
- Autoware.

9.2. Simulating the Self-driving Vehicle

TalTech iseAuto has a simulation model which can be simulated in the Gazebo environment by utilizing its physics and sensors. Nevertheless, Gazebo lacks modern game engine features like Unreal and Unity which gives the power to create a complex virtual environment and realistic rendering.



On the other hand, CARLA and SVL are modern open-source simulators based on the game engines, Unreal and Unity respectively, which also have good compatibility with our AV stack Autoware. Although, comparing these two is beyond our discussion but we selected the SVL as our simulator because of its compatibility with our terrain generator which is Unity. You can find detailed information on the SVL simulator and how to install the latest version here: https://www.svlsimulator.com/.

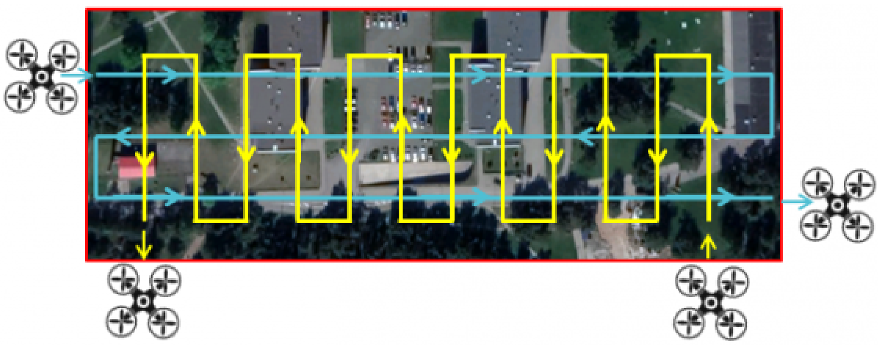


The above figure shows a full map of the simulation workflow and the relation between Autoware and the simulator. Vehicle 3D models and the virtual environment, which are created inside Unity, are imported to the simulator. The simulator allows customizing the environment to create different scenarios such as adding/removing other road users, putting traffic systems, and adjusting the time of day and the weather of the scene. Then, virtual sensors provide information for the perception of the environment. This information is transferred via a ROS bridge to the control software platform to use in perception algorithms for localization and detection. Perception results are used in the Autoware planning section which makes the control commands for the vehicle. These control commands are sent back to the simulator via the ROS bridge to navigate the vehicle inside the simulator.

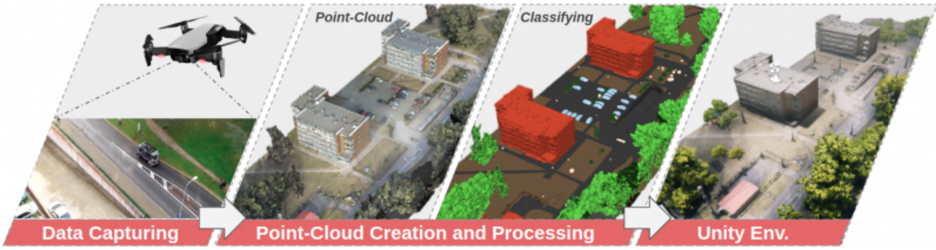
The 3D mesh model of the vehicle should be imported to Unity to define physics components like collider and wheel actuation, in addition, to assign other features like lights and materials for appearance. Finally, the built vehicle exported from Unity is used in the simulator. Later, all the sensor configurations are defined via a JSON file inside the simulator.

9.2.1. Virtual Environment Creation

In order to create a virtual environment as a testbed for simulating the autonomous vehicle, the aerial mapping approach to map the desired environment is needed. In this way, a drone is used to capture images from the real environment, then multiple software techniques are utilized to convert them to a Unity terrain. The images are captured at a grid-based flight path, see the image below. This ensures that the captured images contain different sides of a subject.



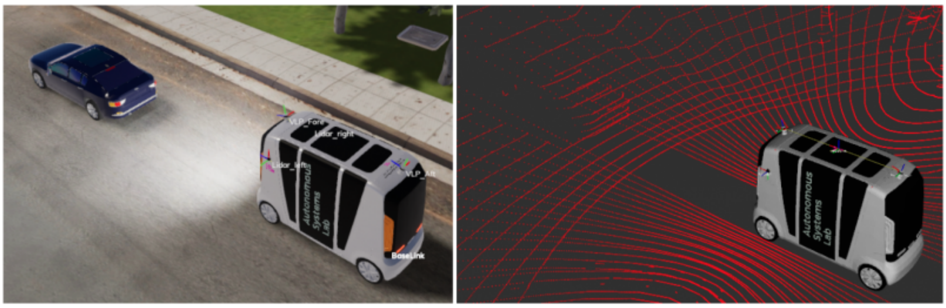
Taking aerial photos is one of the most important steps in the mapping process as it will significantly affect the outcome of the process and the amount of work to be done to process those images. The images taken are georeferenced by the drone. The onboard IMU provides the pictures with the orientation so that later they can be stitched together and used for photogrammetric processing. Third-party software aligns and creates the dense point cloud from the pictures that were captured. Once the dense point cloud is created, the segmentation and classification of the points are needed in order to separate unwanted objects and vegetation from the point cloud data. The below figure shows the three main steps to generate the Unity train from geospatial data.



Now it is ready to load the final map that is built by Unity for SVL simulator.

9.2.2. Run the Simulation

Now, by using a high-fidelity simulator we can simulate different scenarios close to the real to evaluate the control algorithm performance and safety. In terms of defining these scenarios, the SVL simulator provides a python API for spawning different objects like NPC (Non-player character) cars and pedestrians inside the virtual environment with different motion plans.



The above-left figure shows the vehicle inside the simulator that is stopped behind an NPC car, while, at the same time the right figure shows the point cloud of all Lidars that is derived from the current scene in the environment.

9.2.3. Summary

Simulation is a more and more important aspect of developing robots and intelligent vehicles like self-driving cars. The importance is rising in parallel with the complexity of control algorithms and the integration of mechatronic systems in the vehicle. Simulation helps to reduce drastically the development cost and increase the general safety of the end result. It is clear that early prototypes may easily cause accidents if the testing is done on real traffic but if thousands of miles are conducted on the simulations and most of the software bugs and electromechanical incompatibilities are eliminated it is safer to start open road tests. Therefore simulations during the self-driving vehicle development are almost must be today's engineering process.

10. Drones

10.1. Introduction to the UAVs

The UAV - Unmanned Aerial Vehicle is a flying object that there is no person on-board. We used to name it a drone as well.
While saying drone, we usually visualise a quadcopter (i.e. DJI Phantom), but that is very narrowed meaning. Drone or UAV is anything flying RC or autonomously, including other structures like, i.e. helicopter and fixed-wing ones: plane, soarer, flying wings, also many hybrid constructions.

While the drone operator (UAVO) can be a person that manually controls the drone using remote connection, it is also possible that they may create a flight plan (mission) and upload it to the drone's flight controller to let it follow it or even to let it perform independent decisions on how and where to fly. Those are autonomous flights. In any case, there should be a human person that even if the flight is autonomous, it may monitor mission progress and take manual control in case of an emergency.

10.1.1. Flight modes

From this point of view, we consider flight modes of the UAV that are one of the following:

- Remote Control - operator “drives” a drone.
- Mixed - operator “drives” but automation of the flight control may interact with the drone, i.e. introduce collision avoidance, smoothen tilts and so on.
- Autonomous - where drone follows the flight plan (mission).
- Mission plan can also be modified ad-hoc, using onboard decision systems or communication (but human independent, or with the limited impact of the human operator).

10.1.2. Operation modes

From the legal point of view, the relation between the drone and its operator, regardless of the flight mode, as mentioned before, is an operation mode and can be classified as one of the following:

- VLOS – flights within Visual Line of Sight range: operator must be able to see the drone using unaided eye (well, you can really wear glasses if you need one in a regular basis). The operator must be able to operate the drone in RC mode (even if the mission is autonomous just in case of emergency), so seeing your drone as single point some 1km away from you is believed not to be a VLOS, unless you have an eagle eye. Of course, if you need to have a quick peek to the video stream or telemetry display to see flight parameters, it is all valid but please note, when your drone is far away, and you lost its sight, it is not easy to find it back again so you may get into the trouble.
- BVLOS – flights Beyond Visual Line of Sight: operator not necessarily needs to see the drone, but one should be still aware where it is now, using onboard and ground station instrumentation (usually some telemetry, video link, mission control software and so on). BVLOS is both situations when your drone is too far away to be seen (even if not hidden behind another object) or is close enough, but hidden, i.e. around the corner of the building.
- FPV – First Person View flight, when UAVO wears special glasses (or uses a ground display) that presents live transmission from the drone, as seen by the “virtual pilot sitting in the drone's cockpit”. That is the most common case in drone racing.

10.1.3. Summary

In any case, nowadays, the drone is not just only a piece of hardware but the whole ecosystem: growing as there is a demand for more and more complex tasks. It includes hardware, software, human and perhaps in the nearest feature, artificial operators, communication infrastructure and procedures. In the following sections, we go into the details on each of those components.

10.2. UAV platforms

As mentioned in the introduction, the "drone" is frequently misunderstood as a quadcopter. In fact, UAVs origin from fixed-wing devices that mimic real planes far, before first multirotor appeared on the sky.
In the following sections, we discuss features of the particular construction (airframes). Still, to understand it, one needs to understand elementary principals on, why actually something heavier than air can fly.

10.2.1. Aerodynamics principals

In the beginning, it was natural for humankind to assume, nothing heavier than air can fly. However, birds used to break this rule. First observations brought the concept of the bird's wing, as the main feature that enables them to fly. It was particularly clear while observing raptors (eagles, falcons, ospreys) able to soar without a meaningful waving of the wings.
The phenomena that brought people to the sky is called a "lift force" (shortly referenced further as "lift"). A special shape of the wing causes the flow to travel the long way through the upper part, comparing to the flow over a short way, under the wing. That generates perpendicular (well, close to perpendicular) force to the flow direction called lift. Obviously, the existence of the flow is essential to generate lift and keeping it in simple; faster flow generates bigger lift force (that relation is not linear, however, but square, regarding velocity). Air can be considered as a sparse fluid, and fluid mechanics apply here. More about principals and physical model of the lift creation can be found on the Experimental Aircraft Info website [30].

The angle between the incoming airflow and the wing surface affects lift generated (when angle grows, lift increases, as air has to travel on even longer distance on the top surface). It is named Angle of Attack (AOA). But increasing the angle cannot be done infinitely: each wing (construction) has some rated maximum (AOA). When exceeded, lift force suddenly drops, as airflow becomes turbulent causing the wing to stall. Non-laminar airflow is a common reason for low lift force and has been a reason for many serious accidents. Polished wing surface is essential to ensure non-turbulent (laminar) flow, thus, i.e. icing decreases it significantly.
To control an object, 3 axes cross within the centre of gravity of the drone, and each drone must be able to control it. Those are Roll, Pitch and Yaw. Composition of those three rotations can locate drone within 3D space in any direction and position. Controlling each axis requires the ability to apply a force, and it is implemented differently, depending on the airframe. By the aforementioned, we used to consider also thrust as 4th force that enables full control.

10.2.2. Airframes

There are 3 main categories of drone airframes:

1) Fixed-wing: mimicking birds and planes;
2) Helicopters: following large helicopters with underlying DaVinci's project;
3) Multirotors: a pretty new concept, that actually is not directly related to nature or human-made flying object.

10.2.2.1. Fixed-wing

A long time before UAV and drone terms were introduced to the world, the hobbyistsimplemented RC planes that build fundaments for current technologies driving the drone market. The main concept of the fixed-wing is to follow full-scale constructions like passenger aeroplanes, soarers, combat flying wings and military jets. The main source of the lift force are wings (usually two, located symmetrically).

Those constructions also used to have a vertical stabiliser (tail, one in the centre or two by sides) to stabilise direction. This is so much different compared to the birds. Axes are controlled with control surfaces, and thrust is generated with propellers or jet engines. There are many variations of this airframe model but elementary one, mimicking plane, has three main control surfaces:

- ailerons - controlling roll;
- elevators - controlling pitch;
- rudder - controlling yaw.

Many drones (particularly bigger ones) require additional surfaces, helping, i.e. to slow down or to increase lift (Figure ##REF:planectrlsurfaceadv##):

- flaps - when deployed, increase lift and also slow down - flaps work partially as air brakes, but please note, many planes, including soarers/sailplanes, do have separate airbrakes located in the mid-wing, not related to the flaps, while some jets may have it implemented on the wing or even at the tail on their body;
- slats (singular is slot) - provide an additional surface to increase lift - not very common in small and medium UAVs but in the large scale ones, may be essential to increase Maximum Take-Off Mass (MTOM).

Flaps and slats are deployed usually during take-off and landing.

10.2.2.1.1. Flying wing

A flying wing is an evolution of the regular plane, where the whole body has been transferred into the single wing to maximise generated lift. Flying wings have better volume/area to MTOM ratio than regular planes, as virtually almost whole airframe generates lift (Figure 37). In case of the flying wings, control surfaces are integrated and usually limited to just only two of them, integrating ailerons and elevators. It requires mixing of the control channels implemented in the RC controller or the flight controller (or both, depending on the current flight mode). Many industrial and military drones are implemented as a flying wing because of the heavy payload (professional cameras, weapons) they carry. Flying wings do not use rudder nor tail, and that is one of the reasons they're hard to be detected by Doppler radars, as side reflection is shallow. On the other hand, lack of rudder increases stability problems on the straight-line flights with a crosswind, during takeoff and landing. In full-scale construction this problem is tackled with thrust vectoring, usually requiring jet engines. For this reason, many flying wing UAVs introduce side sharklets (small "tails" at the end of each wing), similarly to those introduced by the Airbus company in their A320 series, now present in most of the passenger planes constructed in the world.

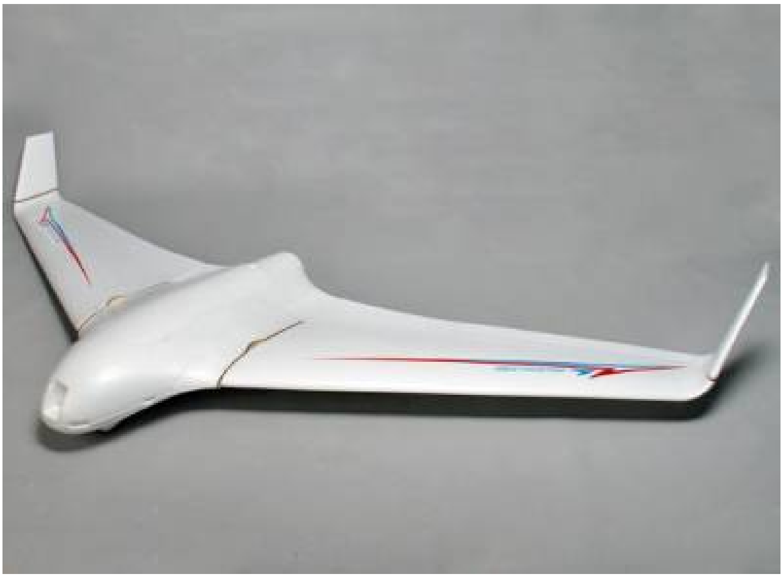


Figure 37. Flying wing (here X8 frame)

10.2.2.1.2. Tail and rudder variations

There are many approaches to improve flight performance and stability. One of the variations that made it popular to the market is V-tail (Figure ##REF:F117##). It integrates rudder and elevator and in case of UAVs requires technology discussed in case of the flying wings, regarding control of the V-tail surfaces.

Figure 38. Lockheed F-117 Nighthawk with V-tail

10.2.2.1.3. Pros and Cons

Each airframe has features and drawback. Here we discuss the most noticeable ones.

Pros:

- Simple flight control in RC mode: RC controllers were designed to handle plans control without extra flight controller (early RC hobbyists);
- Passive generation of the lift force through wings;

▪ Ability to soar/sail without active propulsion or even with no throttle force generation at all (no engine);

▪ Possibility to recover on failure;

▪ Model of the dynamics od such construction is well documented and deeply studied.

Cons:

▪ Cannot hover in one position - drone must move forwards;

▪ Requires runway to take-off and land;

▪ Cannot fly upside down (usually, unless thrust is reasonably bigger than lift force, to replace it to some extent) as wing's section is not symmetrical;

▪ Minimal turning radius exists;

▪ Problems “following” slow objects - a necessity to circuit round followed object if its speed is below critical (minimum) flight speed for the drone;

▪ Fixed wings are fragile to the crosswind.

10.2.2.2. Helicopter

It was Leonardo Davinci's idea, to use a big, screw-like device (aerial screw, Figure 39) to “drill” air and generate an airflow downwards, thus creating lift force oriented upwards.

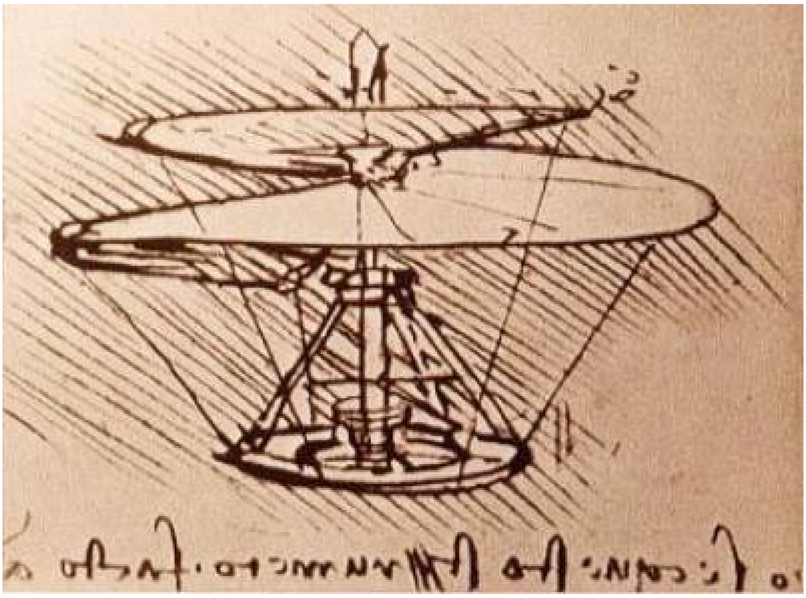


Figure 39. Leonardo's “aerial screw”

This idea has grown in the first half of the XX century into the full scale and models/UAVs, but as helicopter construction is a pretty complex one (both natural and scale), it is not very common to be used as UAV. Helicopter's body mimics a dragonfly, but the nature of the generation of the lift and control is different than in case of insects.
A regular helicopter has a large rotor with at least two blades. Each blade can be rotated parallel to its length, this way changing the lift force generated by each blade. Moreover, each blade can be virtually rotated independently; thus, the main rotor can “vector” the lift, enabling the helicopter to roll and pitch.

To operate helicopter up and down (change total lift) one uses collective pitch, so changing all blades angle of attack (aforementioned rotation parallel to its length) increases or decreases total lift generated by the main rotor (Figure 40).

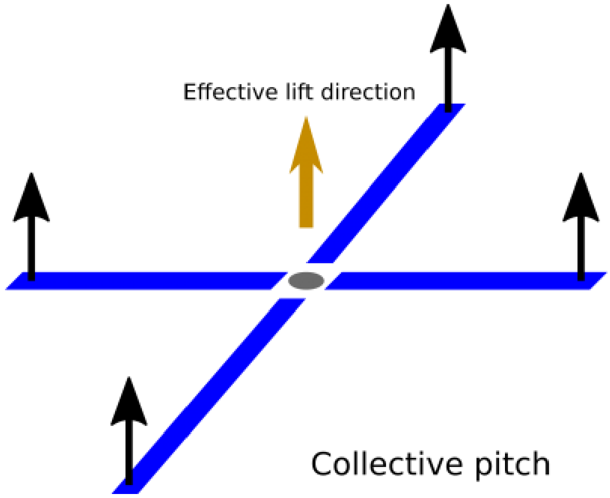


Figure 40. Collective pitch idea in helicopters (main rotor)

To roll and pitch, there is a way to change the position where each blade generates a larger lift, using so-called "cyclic pitch". Angles of the blades are altered while rotating, dynamically (Figure 41), so the same blade generates different lift depending on its current position. That causes the lift to change its effective direction that no longer is perpendicular to the main rotor rotation surface.

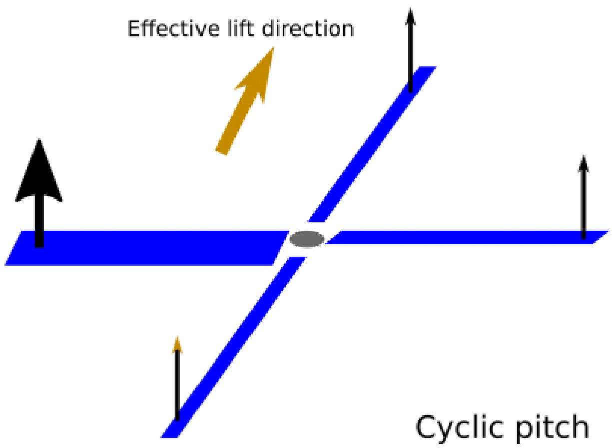


Figure 41. Cyclic pitch idea in helicopters (main rotor)

The most notable part of the helicopter is a mechanism, that drives the main rotor and controls blades (rotor hub, Figure 42).

Figure 42. Rotor hub

In many micro drone constructions, the collective pitch is implemented with the change of the rotation speed of the motor driving the main rotor. This construction, however, excludes cyclic pitch thus rotating in pitch and roll axes is implemented other way (see below, Figure 44) and usually limits the number of rotation axes the device can use while in the air.

Additionally, base helicopter construction has a tail rotor (anti-torque), and its main responsibility is to compensate force generated by the main rotor. The tail rotor is perpendicular to the main rotor and pushes or pulls the tail, thus also enables the helicopter to yaw (Figure 43).

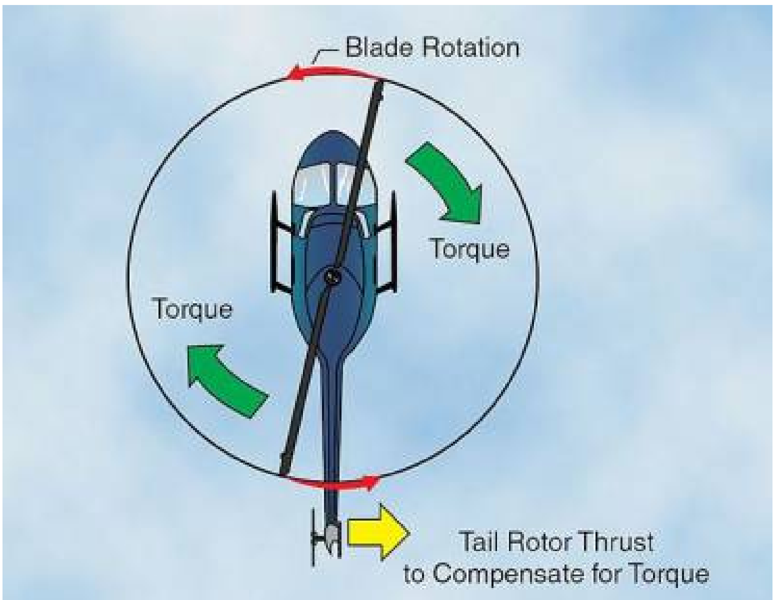


Figure 43. Anti torque tail rotor

In the full-scale helicopters and large UAVs, main rotor and tail rotor are usually driven parallel, as the rotation of one impacts another. Hence, the tail rotor has rotatable blades that can change the force generated even at the constant rotation speed. In case of the tail rotor, all its blades are controlled parallel, that is different than in case of the main rotor where each blade can be virtually controlled independently. In the case of smaller UAVs, the tail rotor motor is usually separate from the main rotor motor and controlled independently of the main rotor with an electronic controller. In large scale helicopters, the tail rotor can be exchanged with the air-jet outlet of the hot gases leaving turbine (or turbines) that drive the main rotor: this seems to be a more efficient solution, as it uses exhaust gases to implement anti-torque force, but also problematic to control thus not very common.

10.2.2.2.1. Dual main rotor helicopter

Torque compensation can be implemented using counterrotation. There are two known solutions:

- coaxial - counter-rotating, pretty common in small RC models (Figure 44), but is also present in full scale ones: Kamov Ka-50;
- tandem - as in well known Boeing CH-47 helicopter - popular Chinook (Figure 45).

Small scale RC helicopters are usually simplified on their construction, not to include tail rotor classically, while rather equipped with two rotors mounted on the coaxial shaft, driven by separate electric motors and counter-rotating. This way torque of one rotor is compensated with a torque of another one. This construction is additionally equipped with a tail rotor that is parallel to the main one, driven by separate, 3rd electric motor, that enables the helicopter to pitch. This construction can only pitch and yaw, cannot roll. Yaw is implemented with a change of the relative rotation speed of two main rotors (Figure 44).

Figure 44. Miniature RC helicopter with coaxial, counterrotating two main rotors

In commercial helicopters, coaxial, counter-rotating main rotors are used in lightweight constructions.

Another solution is used in the heavy lifting helicopters with two main rotors mounted on their endings, so-called "tandem", like i.e. CH-47, where there is no tail rotor at all. Still, both main rotors provide collective and cyclic pitch (Figure 45).

Figure 45. Two rotor helicopter (CH-47 Chinook)

10.2.2.2.2. Flybar

Many scale helicopters introduce the flybar: a coaxially mounted bar, usually with extra mass by its endings, mounted over the main rotor (sometimes parallel, sometimes perpendicular), to stabilise small models, where rotor blades present small inertia, due to their low mass thus causing instability in flight. Introducing a flybar increases helicopter stability but also lowers its manoeuvrability and response.

10.2.2.2.3. Pros and Cons

Each airframe has features and drawback. Here we discuss the most noticeable ones.

Pros:

- Helicopter can hover;
- Can even move backwards;
- There is no minimal turn ratio (as in fixed-wing) and it can pivot in place;
- Uses vertical take-off and landing (VTOL).

Cons:

- Active generation of the lift (far less efficient than a fixed-wing);
- Main rotor failure causes immediate fall, still, there is a rescue procedure called autorotation but so far hard to implement in scale models;
- Complex mechanics and servicing.

10.2.2.3. Multirotors

So far, a quadcopter (multirotor with 4 propellers) is a synonym for a drone or UAV. This construction comes partially from helicopter idea and is simplified a lot as in most cases it uses fixed blades. There is no natural (animal) to mimics, and construction is purely artificial, human-invented. Multirotors can operate freely in 3D space and most cases they use at least 4 motors (eventually less, with force vectoring, i.e. using servomotor). Most popular is the quadcopter construction, but hexacopters (with 6 rotors), octocopters (8 rotors) and even multirotor with 16 motors and propellers (hexadecacopters) are not rare (Figure 47). Lightweight constructions usually do not go beyond the "Hexa" configuration (Figure 46) as motors are the heaviest part of the drone (along with battery pack) and there are limits on the maximum take-off mass (MTOM) inexperienced operator can control.

Figure 46. Hexacopter

Constructions with more than 4 motors have a great feature: the ability to keep flying stable and safely even if one of the motors is down (or even more).
Some modern and usually large quadcopters can also minimise the impact on fall when one of their motors is down. Using 3 motors and self-rotation, such quadcopter can limit its fall velocity to lower damage on impact to the ground. This is not a fully-controlled way to land, however, to minimise damage (i.e. DJI Matrice M300).

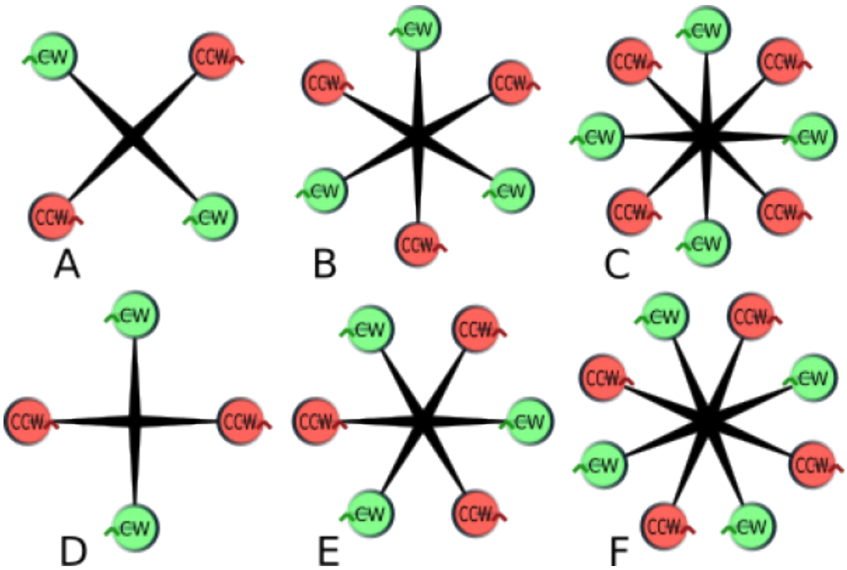


Figure 47. Multirotor variations (selected, but not limited to)

There are dozen of different structures of multirotor airframes, each with particular features and drawbacks. Propellers generate lift, and in most cases, propellers are fixed (there is no pitch variation like in helicopters) and the lift is controlled independently for each motor via changing rotation speed. Composition of all lifts generated drives drone operation. There do exist multirotor, that share the same idea as helicopter's main rotor construction. There is a central motor and change in the lift is controlled via a variable pitch of each propeller. Multirotor requires advanced flight controller to stabilise in the air, using gyroscope and accelerometer (at least). Opposite to the fixed-wing, human operators are unable to control multirotor directly as itrequires at least 100 Hz position update (currently control loop is up to even 32kHz).

Because of the simplicity of building and ready components availability, that they are adaptable for virtually any variation of the multirotor construction, multirotor is the most frequently used construction for UAV even, if its flight dynamics is still hard to model on the theoretical level. Because of lack of detailed model, most of the flight controllers use the PID controller for each degree fo freedom of the copter extensively. PID parameter tuning is related to the particular airframe and usually obtained experimentally. Of course, ready sets provide pre-tuned airframes, and the Internet is full of advice and parameter sets for popular frames, but changes to the payload and centre of gravity can infer stability.

Multirotors are universal and can hover in place as helicopters, yet far more stable. Movement is possible in any direction as most of the constructions are symmetrical. Lift is generated collectively via all motors and propellers.

On Figure 47 there are presented variants for quad-, hexa- and octocopters, where their geometry differs. In general, X-shaped constructions (A, E, F) are more popular over plus-shaped ones(B, C, D), because of two major factors:

- pitch (tilt, roll) of the copter is done by more than one motor that speeds it up, of course, the cost is extra energy;
- from facing camera won't have an arm, motor and propeller in the centre of the field of view.

Aerial operations using a multirotor can be easily explained considering quadcopter as an example. Principals of the operations are extendable straight forwards to the hexa-, octa-, and more propellers. The general rule is to variate the rotation speed of the motors, thus affecting generated lift and this way to pitch the multirotor in the desired direction (Figure 48). Yawing uses inertia to rotate; thus, this operation is the least efficient in case of multirotor. On Figure 48 we present motor's rotation speed variation to obtain the desired effect of the pitch, yaw and roll rotations.

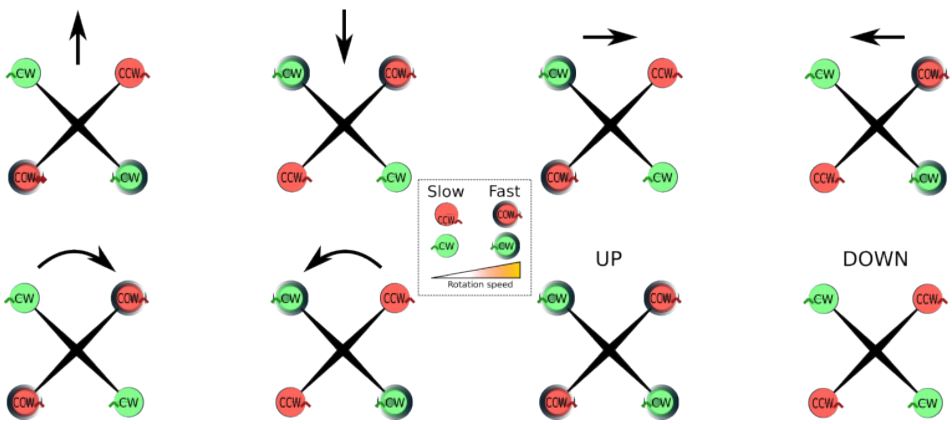


Figure 48. Multirotor aerial rotations and moves and their physical principals

As a multirotor drone can virtually fly in any direction, yaw rotations are not frequently used, yet in case of drone equipment is directional (i.e. camera mounted only in front of the drone and not rotatable) ability to yaw is still essential.

In Figure 47 one can observe that any multirotor has a + (plus, as in 47D) or X version (as in 47A). X version is popular in drone racing and video filming, as front-mounted camera view is not affected with front arm (as in case of the plus configuration) yet and this is the majority of the multirotor UAVs. Plus configurations are considered obsolete and niche.

10.3. Navigation

10.3.1. Global Navigation Satellite Systems GNSS

10.3.2. Introduction to the GNSS

Global Navigation Satellite Systems (short GNSS) are useful to position an object (here drone) in 3D space, mostly outdoors.
Actually, 2D, planar (longitude/latitude) positioning is quite good and in most applications suitable, vertical positioning used to be inaccurate, so most drones use a different strategy to check their altitude, mostly measuring atmospheric pressure changes (using barometer). UAVs usually operate on long distances (some meter to even thousands of kilometres), so satellite-based positioning seems to be a reasonable choice. As receivers became cheaper, they appeared in almost all drones that operate in autonomous mode and in many of those that are manually controlled, to smoothen operations, provide rescue features (i.e. Return to Home function) to ensure basic and advanced features like, i.e. geofencing, collision avoidance and so on. Current, modern GNSS receivers operate with multiple constellations parallel, delivering even better accuracy of the planar positioning. Still to get reliable positioning with high accuracy, one needs to ensure good satellite visibility.

There is several factors, decreasing positioning that every UAV operator should be aware. There is a number of factors, decreasing positioning that every UAV operator should be aware, as they may lead to incidents and accidents:

- Time synchronization - it is crucial to have common time-base for both sender and receiver. Time synchronization occurs during so-called "obtaining fix" and in short is based on error minimization between position estimation based on at least four (usually much more) satellites. Time synchronization is also performed periodically, as satellite time-base is considered as a reference one, but receiver implementation varies in quality. Thus you may observe periodical degradation of the accuracy in reference conditions, because of the de-synchronization of the receiver.
- Selected Availability (SA) - as introduced by the constellation owner to interfere radio signal of the satellites, thus decrease the accuracy the controlled way. This was widely used in case of the American GPS (Navstar) until the first war in the Persian Gulf when US Army had to switch to the commercial receivers (affected by SA) because of lacks of delivery of the military products (that had SA corrected internally). Since then, GPS positioning became much more useful because of the increased accuracy of the positioning, once SA was disabled or at least reduced.
- Ionosphere delay - as solar radiation has a strong impact on the ionic sphere of the Earth, radio signal passing through it may experience deflection (thus delays). That is the second, natural phenomena, decreasing accuracy. Solar radiation is given by the KP Index that can be read close to real time and is related to solar activity. With KP over 3, flying UAV is not advised, or at least try to avoid flying in a tight environment when filming, i.e. northern lights as you may experience sudden shifts of your drone even some dozen of meters. You can read the current KP index and forecast, i.e. here: Aurora Service.
- Troposphere - has some minor impact (comparing to the mentioned above) yet it does exist. The troposphere is relatively thin, comparing, i.e. to the ionosphere. Advanced GPS receivers may use a built-in calendar to provide thermal compensation, based on the time and current position as using average temperature for the obtained location.
- Ephemeris error - sometimes, satellite orbit is altered and satellite is not where it is intended to be, so the distance between satellite and receiver is affected. GPS receiver is unaware of the position deviation; thus, it has an impact on the positioning accuracy.

Some of those phenomena can be handled tricky way (i.e. ionosphere deflection impacts different way signals with different frequency thus Glonass system can handle this issue almost real-time by calculating error, differential-based way) while others can be applied post-factum or live using corrections sent via other channels.
The detailed description of the impact of the aforementioned factors for accuracy and performance is presented below in section **GNSS Performance and Accuracy**.

10.3.3. GNSS History

10.3.3.1. US GPS NAVSTAR

- The United States Navy conducted satellite navigation experiments in the mid-1960s to track US submarines carrying nuclear missiles. With six satellites orbiting the poles, submarines were able to observe the satellite changes in Doppler and pinpoint the submarine's location within a matter of minutes.
- In the early 1970s, the Department of Defense (DoD) wanted to ensure a robust, stable satellite navigation system would be available. Embracing previous ideas from Navy scientists, the DoD decided to use satellites to support their proposed navigation system. DoD then followed through and launched its first Navigation System with Timing and Ranging (NAVSTAR) satellite in 1978.
- The 24 satellite system became fully operational in 1993. When selective availability was lifted in 2000, GPS had about a five-meter (16 ft) accuracy.
- The latest stage of accuracy enhancement uses the L5 band and is now fully deployed. GPS receivers released in 2018 that use the L5 band can have much higher accuracy, pinpointing to within 30 centimetres or 11.8 inches.

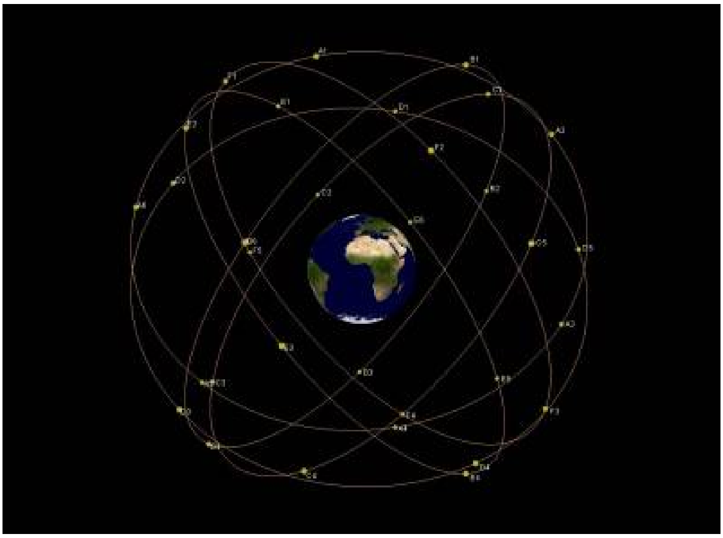


Figure 49. GPS Constellation in space

10.3.3.2. RF GLONASS

- The first proposal to use satellites for navigation was made by V.S.Shebashevich in 1957. This idea was born during the investigation of the possible application of radio-astronomy technologies for aeronavigation. Further investigations were conducted in a number of the Soviet institutions to increase the accuracy of navigation definitions, global support, daily application and independence from weather conditions. The research results were used in 1963 for an R&D project on the first Soviet low-orbit “Cicada” system.
- In 1967 the first navigation Soviet satellite “Cosmos-192” was launched. The navigation satellite provided continuous radio navigation signal transmission on 150 and 400 MHz during its active lifetime.
- he “Cicada” system of four satellites was commissioned in 1979. The GLONASS system

was formally declared operational in 1993. In 1995 it was brought to a fully operational constellation (24 GLONASS satellites of the first generation).

- In 2008 "Cicada" and "Cicada-M" users started to use GLONASS system and the operation of those systems was halted. The low-orbit systems couldn't meet the requirements of a great number of users.

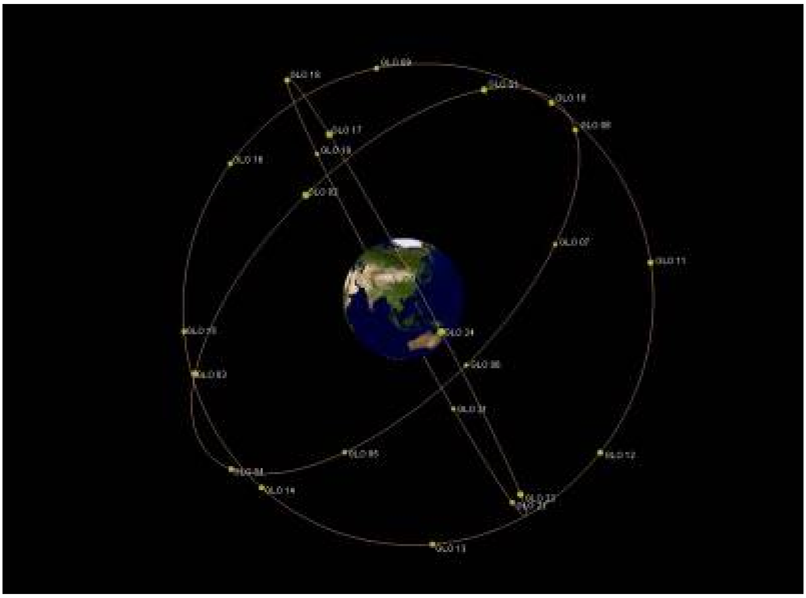


Figure 50. Glonass Constellation in space

10.3.3.3. EU GALILEO

- The first Galileo test satellite, the GIOVE-A, was launched 28 December 2005, while the first satellite to be part of the operating system was launched on 21 October 2011.
- As of July 2018, 26 of the planned 30 active satellites are in orbit. Galileo started offering Early Operational Capability (EOC) on 15 December 2016, providing initial services with a weak signal and is expected to reach Full Operational Capability (FOC) in 2019.
- The complete 30-satellite Galileo system (24 operational and 6 active spares) is expected by 2020.
- It is expected that the next generation of satellites will begin to become operational by 2025 to replace older equipment. Older systems can then be used for backup capabilities.

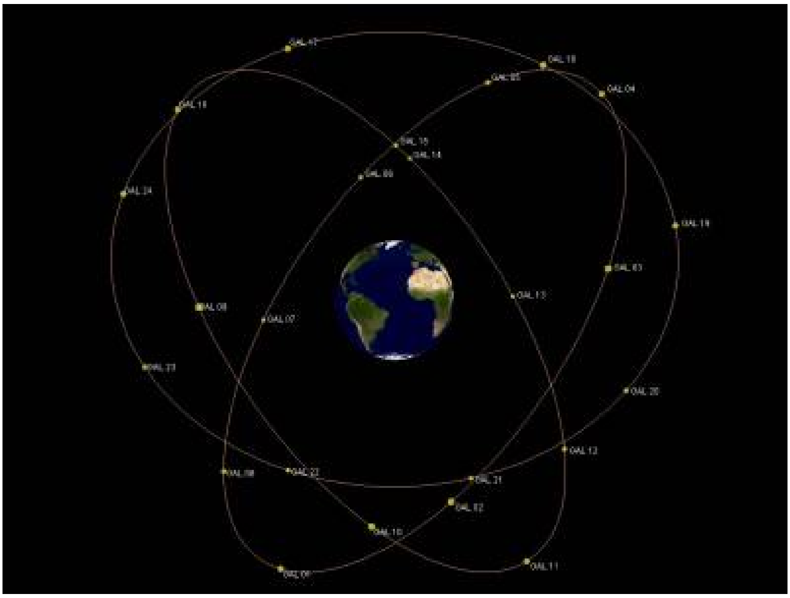


Figure 51. Galileo Constellation in space

10.3.3.4. CHINA BeiDou (BDS)

- It consists of two separate satellite constellations. The first BeiDou system, officially called the BeiDou Satellite Navigation Experimental System and also known as BeiDou-1, consists of three satellites which since 2000 has offered limited coverage and navigation services, mainly for users in China and neighbouring regions. Beidou-1 was decommissioned at the end of 2012.
- The second generation of the system, officially called the BeiDou Navigation Satellite System (BDS) and also known as COMPASS or BeiDou-2, became operational in China in December 2011 with a partial constellation of 10 satellites in orbit.
- Since December 2012, it has been offering services to customers in the Asia-Pacific region.
- On December 27, 2018, Beidou-3 officially began to provide global services.

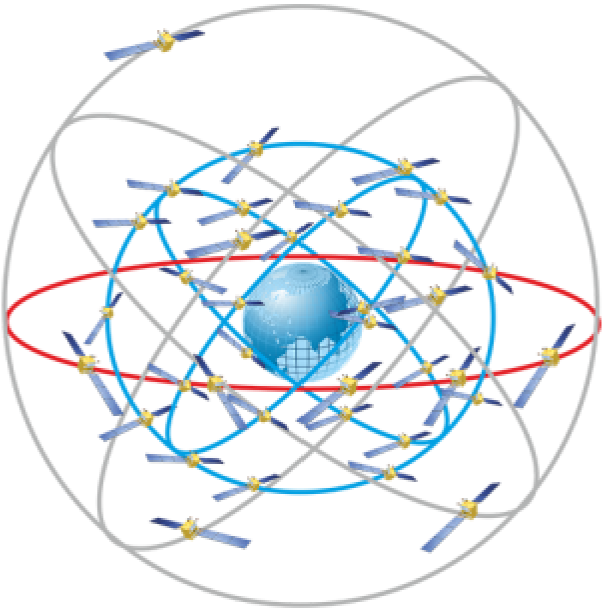


Figure 52. BeiDou Constellation in space

10.3.4. GNSS SEGMENTS

GNSS satellite systems consist of three major components or "segments": **space segment**, **control segment** and **user segment**.

Space Segment The space segment consists of GNSS satellites, orbiting about 20,000 km above the earth. Each GNSS has its own "constellation" of satellites, arranged in orbits to provide the desired coverage. Each satellite in a GNSS constellation broadcasts a signal that identifies it and provides its time, orbit and status.

Control Segment The control segment comprises a ground-based network of master control stations, data uploading stations and monitor stations; in the case of GPS, two master control stations (one primary and one backup), four data uploading stations and 16 monitor stations, located throughout the world. In each GNSS system, the master control station adjusts the satellites' orbit parameters and onboard high-precision clocks when necessary to maintain accuracy. Monitor stations, usually installed over a broad geographic area, monitor the satellites' signals and status and relay this information to the master control station. The master control station analyses the signals then transmits orbit and time corrections to the satellites through data uploading stations.

User Segment The user segment consists of equipment that processes the received signals from the GNSS satellites and uses them to derive and apply location and time information. The equipment ranges from smartphones and handheld receivers to sophisticated, specialized receivers used for high-end survey and mapping applications.

GNSS Antennas GNSS antennas receive the radio signals that are transmitted by the GNSS satellites and send these signals to the receivers. GNSS antennas are available in a range of shapes, sizes and performances. The antenna is selected based on the application. While a large antenna may be appropriate for a base station, a lightweight, low-profile aerodynamic antenna may be more suitable for aircraft or Unmanned Aerial Vehicles (UAV) installations. Figure 8 presents a sampling of GNSS antennas.

GNSS Receivers Receivers process the satellite signals recovered by the antenna to calculate position and time. Receivers may be designed to use signals from one GNSS constellation or more than one GNSS constellation. Receivers are available in many form factors and configurations to meet the requirements of the varied applications of GNSS.

GNSS Augmentation Positioning based on standalone GNSS service is accurate to within a few meters. The accuracy of standalone GNSS, and the number of available satellites, may not be adequate for the needs of some users. Techniques and equipment have been developed to improve the accuracy and availability of GNSS position and time information.

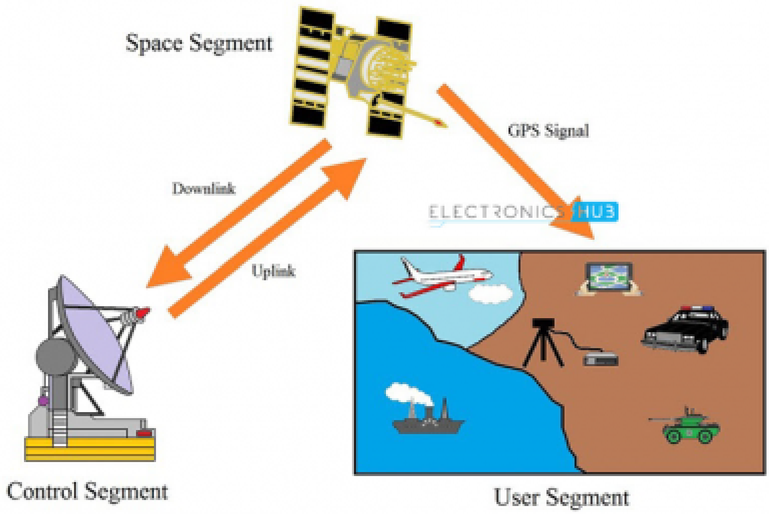
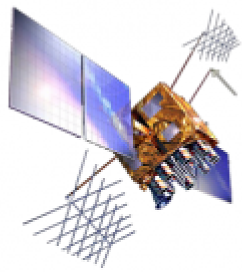


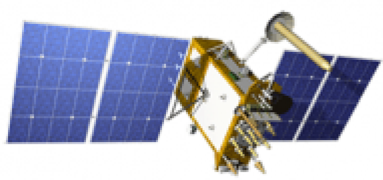
Figure 53. GNSS Segments

10.3.4.1. GPS terrestrial segment



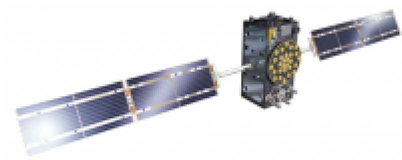
- 33 in-orbit spacecraft;
- Operator AFSPC;
- Type military, civilian,
- Orbital altitude: 20,180 km;
- 6 orbital planes MEO;
- Satellite lifetime: 10 years;
- Satellite mass: 1080 kg;
- Satellite body dimensions: 1,9 m × 1.93 m × 1.52 m;
- Accuracy 500-30 cm;
- Coverage Global.

10.3.4.2. GLONASS terrestrial segment



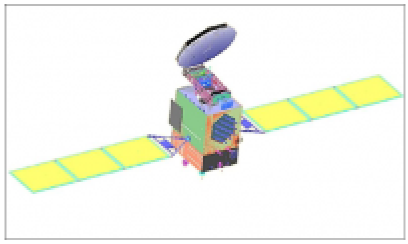
- 26 in-orbit spacecrafts;
- Operator Roskosmos;
- Type military, civilian;
- Orbital altitude: 19 130 km;
- 3 orbital planes MEO;
- Satellite lifetime: 10 years;
- Satellite mass: 1450 kg;
- Accuracy 2.8-7.38 m;
- Coverage Global.

10.3.4.3. Galileo terrestrial segment



- 30 in-orbit spacecrafts;
- Operator GSA, ESA;
- Type civilian, commercial;
- Orbital altitude: 23,222 km;
- 3 orbital planes MEO;
- Satellite lifetime: >12 years;
- Satellite mass: 675 kg;
- Satellite body dimensions: 2.7 m × 1.2 m × 1.1 m;
- Span of solar arrays: 18.7 m;
- Power of solar arrays: 1.5 kW;
- Accuracy 1 m (public), 1 cm (encrypted);
- Coverage Global.

10.3.4.4. BeiDou terrestrial segment



- 33 in-orbit spacecrafts;
- Operator CNSA;
- Type military, commercial;
- Orbital altitude: 23,222 km;
- Orbital planes MEO, IGSO, GEO;
- Satellite lifetime: >12 years;
- Satellite mass: 675 kg;
- Accuracy 10 m (public) 10 cm (encrypted);
- Coverage Global.

10.3.4.5. GNSS systems comparison

All modern and operating GNSS systems like GPS, GLONASS, Galileo or BeiDou which were developed by different countries and organizations use terrestrial segment containing satellites orbiting over the Earth. Each satellite constellation occupies their own unique orbit segments. The entire view of GNSS constellation is present in the picture above. Modern positioning and timing modules have evolved to take advantage of multiple GNSS constellations at once. Combining multiple satellite systems improves the availability of signals, gives operators more access and increases accuracy.

Figure 54. GNSS Systems

10.3.5. GPS Signals

The generated signals onboard the satellites are based or derived from generation of a fundamental frequency ƒo=10.23 MHZ. The signal is controlled by an atomic clock and has stability in the range of 10−13 over one day. Two carrier signals in the L-band, denoted L1 and L2, are generated by integer multiplications of ƒo. The carriers L1 and L2 are biphase modulated by codes to provide satellite clock readings to the receiver and transmit information such as the orbital parameters. The codes consist of a sequence with the states +1 or -1, corresponding to the binary values 0 or 1. It contains information on the satellite orbits, orbit perturbations, GPS time, satellite clock, ionospheric parameters, and system status messages. The modulation of L1 by P-code, C/A-code and navigation message (D), is done using the quadrature phase-shift keying (QPSK) scheme. The C/A-code is placed on the LI carrier with 90° offset from the P-code since they have the same bit transition epochs. For the L1 and L2 we have:

```
L1(t) = a1P(t)W(t)cos(2πf1t)+a1C/A(t)D(t)sin(2πf1t)
L2(t) = a2P(t)W(t)cos(2πf2t)
```

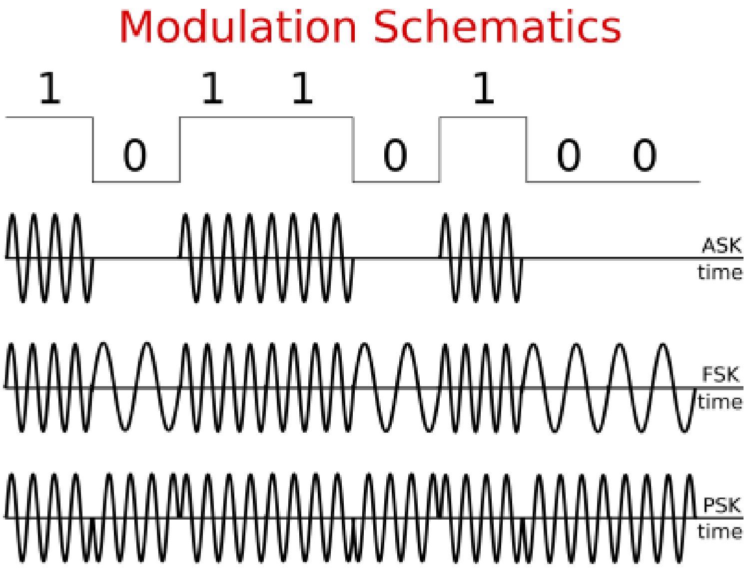


Figure 55. GPS signal modulation

GPS signals in Space The signal broadcast by the satellite is a spread spectrum signal, which makes it less prone to jamming. The basic concept of the spread spectrum technique is that the information waveform with small bandwidth is converted by modulating it with a large-bandwidth waveform. The navigation message consists of 25 frames with each frame containing 1500 bit, and each frame is subdivided into 5 sub-frames with 300 bit. The control segment periodically updates the information transmitted by the navigation message. It is well known that the presence of dual-frequency measurements (L1 and L2) has good advantages to eliminate the effect of the ionosphere and enhance the ambiguity resolution, especially for the high precision measurements.

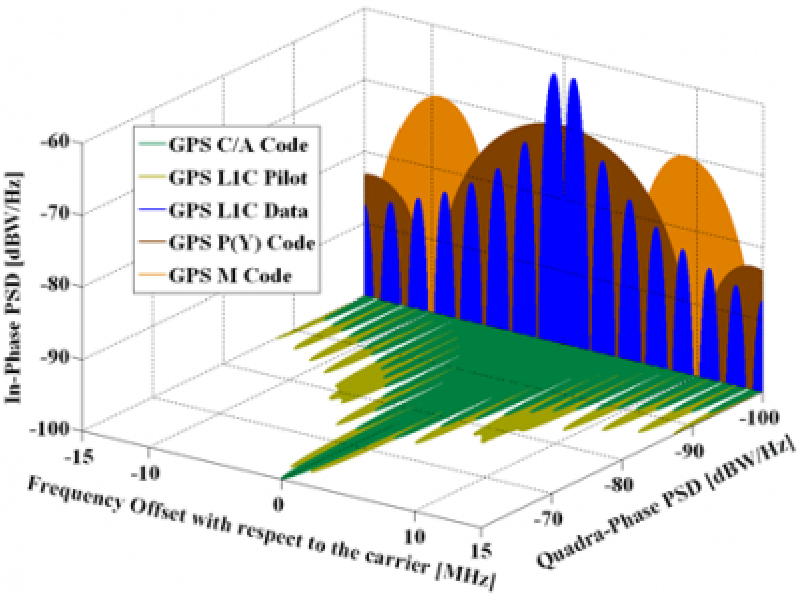


Figure 56. GPS signal spectrum

10.3.6. Glonass signals

Glonass transmit C/A-code on L1, P-code on L1 and L2. Glonass observables (code and phase) are similar to GPS. The main difference between GPS and GLONASS is that GLONASS uses Frequency Division Multiple Access (FDMA) technology to discriminate the signals of different satellites. Still, GPS and Galileo use (Code Division Multiple Access, CDMA) to distinguish between the satellites. All Glonass satellites transmit the same C/A- and P-codes, but each satellite has slightly different carrier frequencies.

```
?_1^? = 1602+0.5625.n MHz
?_2^?  = 1246+0.4375.n MHz
                 with
(?_1^?)/(?_2^? )=9/7
```

where n is the frequency channel number $1 \leq n \leq 24$, covering a frequency range in L1 from 1602.5625MHz to 1615.5MHz.

- The navigation message is contained in so-called subframes, which have a duration of 2.5 minutes.
- Each subframe consists of five frames with a duration of 30 seconds.
- The navigation message contains information, similar to GPS navigation message, about the satellite orbits, their clocks, among others.

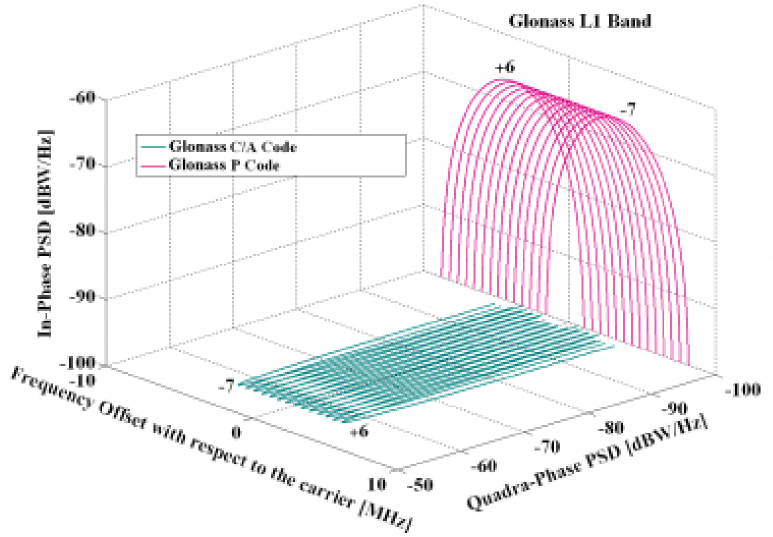


Figure 57. Glonass signal spectrum

10.3.7. Galileo signals

Galileo provides several navigation signals in right-hand circular polarization (RHCP) in the frequency ranges of 1164–1215 MHz (E5a and E5b), 1260–1300 MHz (E6) and 1559–1592 MHz (E2-L1-E1) that are part of the Radio Navigation Satellite Service (RNSS) allocation. All Galileo satellites share the same nominal frequency, making use of code division multiple access (CDMA) techniques. Galileo uses a different modulation scheme for its signals, the binary offset carrier (BOC) and quadrature-phase skip keying (QPSK).

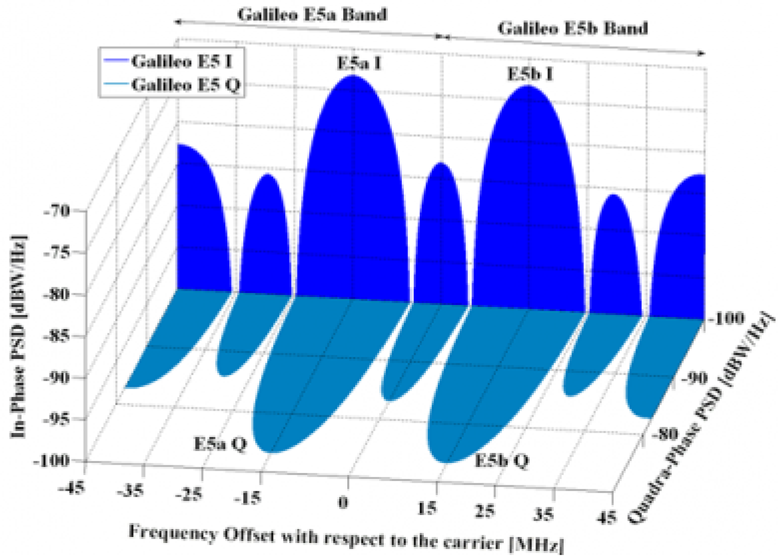


Figure 58. Galileo signal spectrum

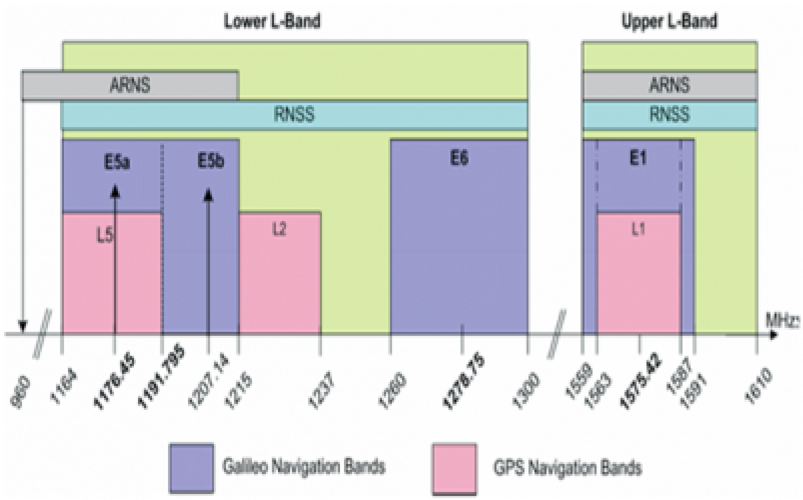


Figure 59. Galileo signal bands

10.3.8. BeiDou signals

BeiDou transmits navigation signals in three frequency bands: B1, B2, and B3, which are in the same area of L-band as other GNSS signals. To benefit from the signal interoperability of BeiDou with Galileo and GPS China announced the migration of its civil B1 signal from 1561.098 MHz to a frequency centered at 1575.42 MHz — the same as the GPS L1 and Galileo E1 civil signals — and its transformation from a quadrature phase-shift keying (QPSK) modulation to a multiplexed binary offset carrier (MBOC) modulation similar to the future GPS L1C and Galileo's E1.

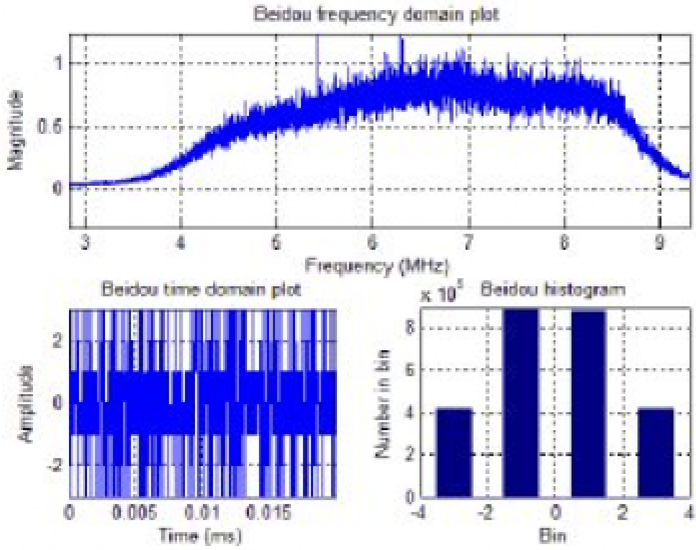


Figure 60. BeiDou signal spectrum

10.3.9. GNSS signal processing

The main function of the signal processor in the receiver is the reconstruction of the carriers and extraction of codes and navigation messages. After this stage, the receiver performs the Doppler shift measurement by comparing the received signal by a reference signal generated by the receiver. Due to the motion of the satellite, the received signal is Doppler shifted. The code ranges are determined in the delay lock loop (DLL) by using code correlation. The correlation technique provides all components of bi-modulated signals. The correlation technique is performed between the generated reference signal and the received one. The signals are shifted concerning time so that they are optimally matched based on mathematical correlation. The GNSS receiver could be designed to track the different GNSS signals and could be of many types:

- The first type could process all GNSS signals GPS L1, L2, L5 and Galileo OS, CS using L1, E5 and E6 and also Glonass L1 and L2;
- The second type uses free signal and codes, GPS L1 and L2C and Galileo OS, on L1 and E5;
- The third type uses L1 and E5;
- Forth type uses GPS L1 and L2 (which are already in the market);
- Fifth type uses GPS and Glonass signals (which already exist).

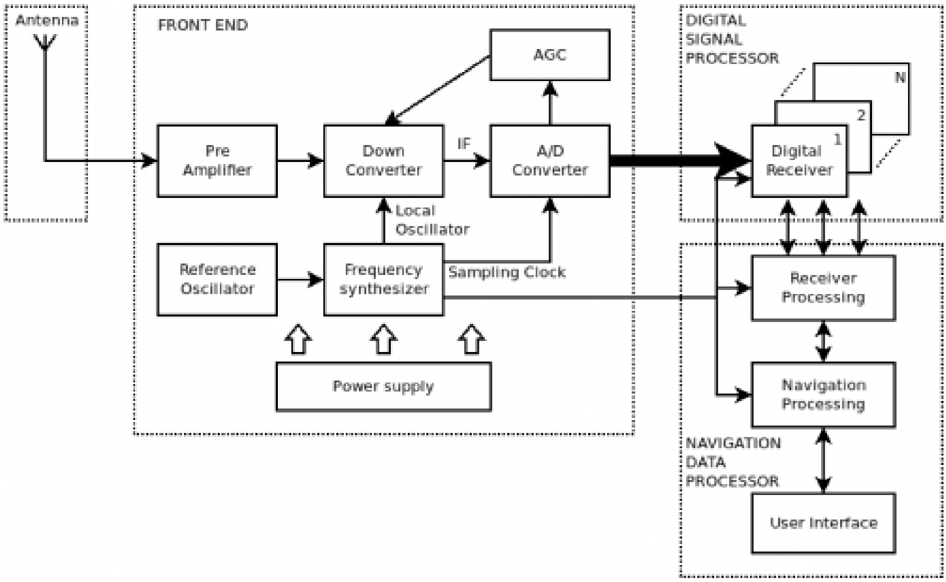


Figure 61. GNSS Receiver block diagram

10.3.10. GNSS differential position

There is an increased interest in differential positioning due to the numerous advantages of wireless communications and networks. Most of the errors that affect GNSS are common between the receivers, which observe the same set of satellites. Thus, by making differential measurement between two or more receivers, most of these errors could be cancelled. The basic concept of differential position is the calculation of position correction or range correction at the reference receiver and then sending this correction to the other receiver via radio link.

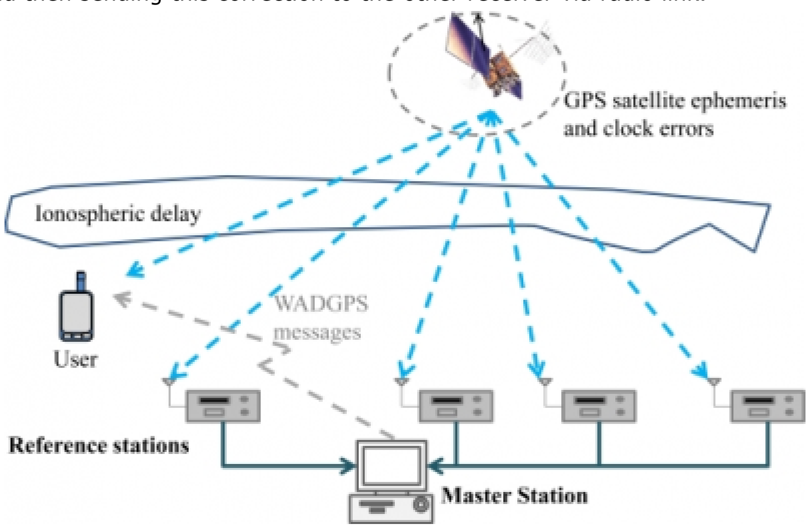


Figure 62. GNSS differential position

10.3.11. GNSS Wide Area Augmentation System (WAAS)

Wide Area Augmentation System (WAAS) is a new augmentation to the United States Department of Defense's (DoD) Global Positioning System (GPS) that is designed to enhance the integrity and accuracy of the basic GPS capability. The WAAS uses geostationary satellites to receive data measured from many ground stations, and it sends information to GPS users for position correction. Since WAAS satellites are of the geostationary type, the Doppler frequency caused by their motion is very small. Thus, the signal transmitted by the WAAS can be used to calibrate the sampling frequency in a GPS receiver. The WAAS signal frequency is at 1575.42 MHz. The WAAS services are available on both L1 and L5.

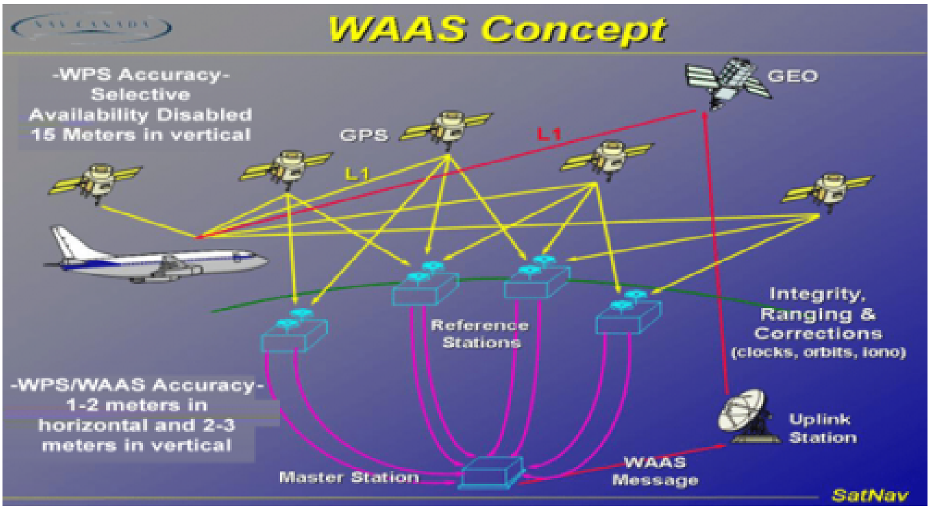


Figure 63. WAAS concept

10.3.12. GNSS Correction Systems

Selection of the appropriate augmentation method or correction service depends on the performance required for vehicle or aircraft navigation software. There are essentially four levels of positioning: standalone uncorrected; positioning derived from publicly available correction services such as the WAAS network in North America or Europe's EGNOS system; positioning solutions derived from globally available subscription-based L-band services; and regional/ local RTK network solutions.

Standalone uncorrected and WAAS/EGNOS type solutions provide position accuracy ranging from 1-10 meters. On the other end of the scale, RTK correction networks provide the most accurate centimetre-level solutions. While L-band solutions deliver corrections directly to the GNSS receiver via satellite, RTK solutions require a base station and a radio to get the corrections needed, limiting operator flexibility and increasing total system cost and complexity.

With subscription-based L-band correction services, users receive Precise Point Positioning (PPP) corrections to help mitigate and remove measurement errors and position jumps. PPP solutions utilize modeling and correction products including precise satellite clock and orbit data to enhance accuracy.

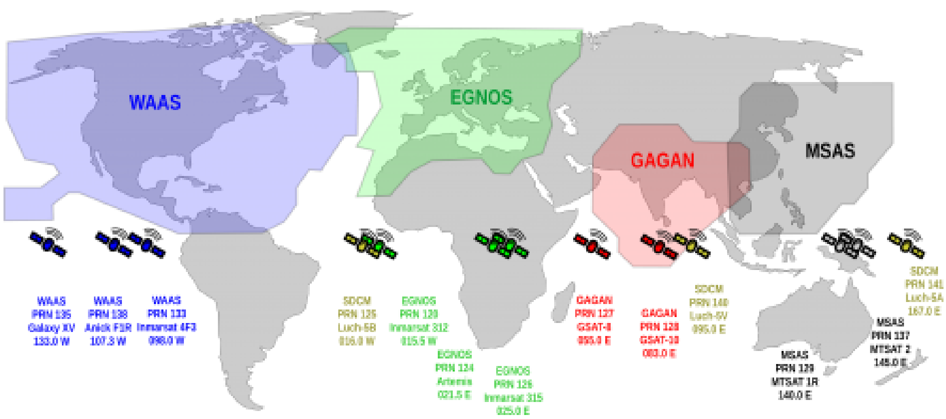


Figure 64. GNSS Positioning correction system concept

10.3.13. GNSS EGNOS

The European Geostationary Navigation Overlay Service (EGNOS) is being developed by the European Space Agency (ESA), for the Safety of Air Navigation (Eurocontrol). EGNOS will complement the GNSS systems. It consists of three transponders installed in geostationary satellites and a ground network of 34 positioning stations and four control centers, all interconnected. EGNOS as WAAS broadcast the differential corrections to the GNSS users through Geostationary satellites, in the European region and beyond.

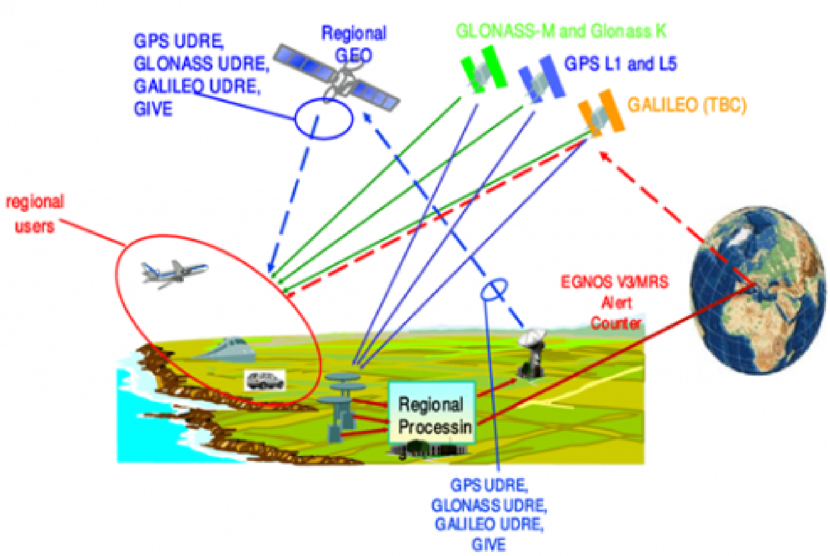


Figure 65. EGNOS concept

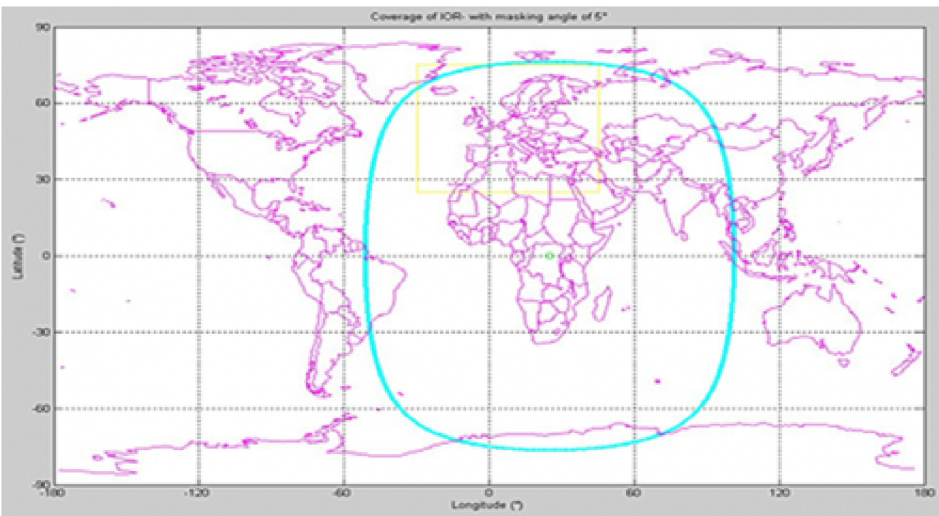


Figure 66. EGNOS range

Entire EGNOS system contain **Ground Segment**, **Space Segment**, **Support segment**, **Space Segment** and **User Segment**.

10.3.13.1. Ground segment

A network of 40 Ranging Integrity Monitoring Stations (RIMS), 2 Mission Control Centres (MCC), 6 Navigation Land Earth Stations (NLES), and the EGNOS Wide Area Network (EWAN), which provides the communication network for all the components of the ground segment.

- 40 RIMS: the main function of the RIMS is to collect measurements from GPS satellites and transmit these raw data each second to the Central Processing Facilities (CPF) of each MCC. The configuration used for the initial EGNOS OS includes 40 RIMS sites located over a wide geographical area.
- 2 MCC: receive the information from the RIMS and generate correction messages to improve satellite signal accuracy and information messages on the status of the satellites (integrity). The MCC acts as the EGNOS system's 'brain'.
- 6 NLES: the NLESs (two for each GEO for redundancy purposes) transmit the EGNOS message received from the central processing facility to the GEO satellites for broadcasting to users and to ensure the synchronization with the GPS signal.

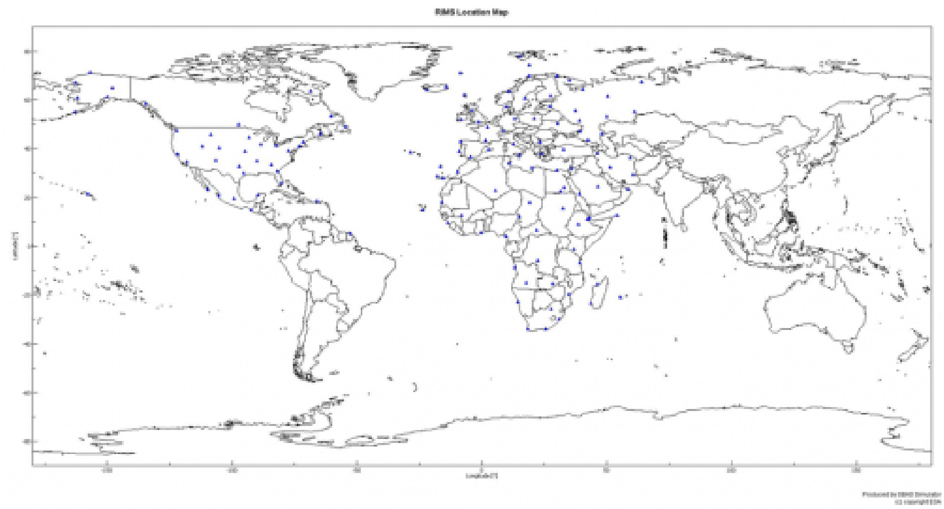


Figure 67. GNSS RIM

10.3.13.2. Support segment

In addition to the stations/centers, the system has other ground support installations that perform the activities of system operations planning and performance assessment, namely the Performance Assessment and Checkout Facility (PACF) and the Application Specific Qualification Facility (ASQF) which are operated by the EGNOS Service Provider (ESSP).

- PACF: provides support to EGNOS management in such area as performance analysis, troubleshooting and operational procedures, as well as upgrade of specification and validation, and support to maintenance.
- ASQF: provides civil aviation and aeronautical certification authorities with the tools to qualify, validate and certify the different EGNOS applications.

10.3.13.3. Space Segment

Composed of three geostationary satellites broadcasting corrections and integrity information for GPS satellites in the L1 frequency band (1575,42 MHz). This space segment configuration provides a high level of redundancy over the whole service area in case of a geostationary satellite link failure. EGNOS operations are handled in such a way that, at any point in time, at least two of the three GEOs broadcast an operational signal.

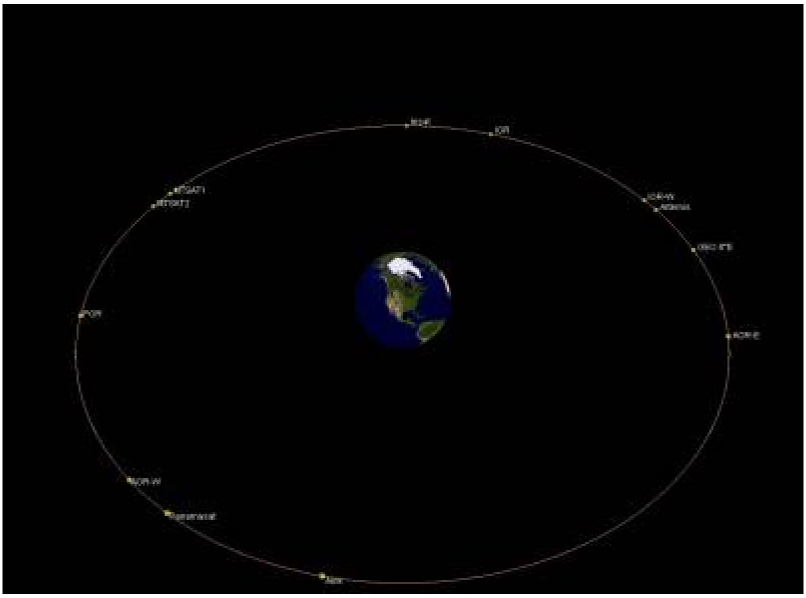


Figure 68. SBAS Constellation in space

10.3.13.4. User Segment

The EGNOS User segment is comprised of EGNOS receivers that enable their users to compute their positions with integrity accurately. To receive EGNOS signals, the end-user must use an EGNOS-compatible receiver. Currently, EGNOS compatible receivers are available for such market segments as agriculture, aviation, maritime, rail, mapping/surveying, road a location-based service (LBS).

10.3.14. GNSS RTK Network

RTK network concept is similar to the WADGNSS, but the reference stations are generally distributed over a regional area, and the network control centre is responsible for transmitting the phase measurement correction to the GNSS user (rover receiver). Mobile wireless networks are generally used in this type of applications due to the need for duplex communication where the rover receiver should send the approximate position initially to the network processing center. The network processing center computes VRS observations and sends it to the user. The number of reference stations in the single RTK approach is 30 stations in 10,000 km^2.

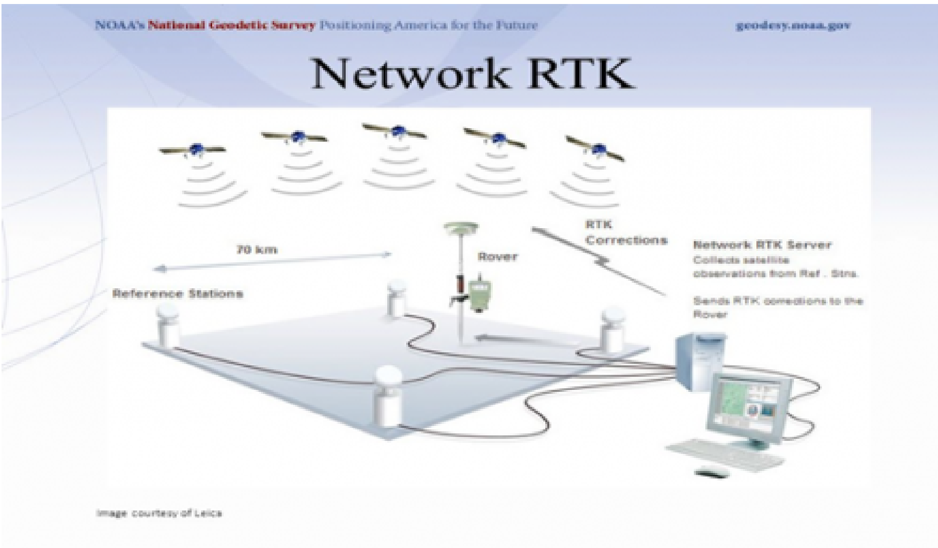


Figure 69. GNSS RTK positioning correction system

10.3.15. GNSS Performance and Accuracy

Four parameters are used to characterize GNSS performance which is based on the RNP specification:

- **Accuracy**: The accuracy of an estimated or measured position of a craft (vehicle, aircraft, or vessel) at a given time is the degree of conformance of that position with the true position, velocity and/or time of the craft. Since accuracy is a statistical measure of performance, a statement of navigation system accuracy is meaningless unless it includes a statement of the uncertainty in a position that applies.
- **Availability**: The availability of a navigation system is the percentage of time that the services of the system are usable by the navigator. Availability is an indication of the ability of the system to provide usable service within the specified coverage area. Signal availability is the percentage of time that navigation signals transmitted from external sources are available for use. It is a function of both the physical characteristics of the environment and the technical capabilities of the transmitter facilities.
- **Continuity**: The continuity of a system is the ability of the total system (comprising all elements necessary to maintain craft position within the defined area) to perform its function without interruption during the intended operation. More specifically, continuity is the probability that the specified system performance will be maintained for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation.
- **Integrity**: Integrity is the measure of the trust that can be placed in the correctness of the information supplied by a navigation system. Integrity includes the ability of the system to provide timely warnings to users when the system should not be used for navigation.

The basic idea of GNSS systems is establishing a satellite network in which each satellite sends a signal at a defined time to receivers. The distance from the satellite to the receiver can be calculated by measuring the time difference from the transmitter to receiver. Using at least 4 satellites simultaneous the 3D Position of the receiver (vertical and horizontal) can be calculated if the position of each satellite is known. The accuracy of GNSS Systems is influenced by the realization of the needed infrastructure, causing the influences on the transmitted signals that make the position calculation possible. Satellites used for GNSS Systems are moving at approx. 4 km per seconds (to the earth) under varying conditions. Due to the movement of the receiver and the transmitter, there is the need to take a look at the factors that determine the accuracy of GNSS Systems.

The positioning accuracy depends on many factors. Position and time error given by GPS receivers are influences by:

- Ionospheric delay - disturbances in the speed of propagation of signals from satellites in the ionosphere (error about 7 m);
- Tropospheric delay - an analogous phenomenon in the troposphere caused by changes in humidity, temperature and air pressure (± 0.5 m);
- Ephemeris error - differences between the theoretical and actual position of the satellites (± 2.5 m);
- satellite clock inaccuracy (± 2 m);
- receiving reflected signals that reach the receiver by other routes than directly from the satellite (± 1 m);
- Receiver errors - noise disrupting the transmission, inaccuracies in the calculation procedures in the software (± 1 m);
- US Department of Defense deliberate action. To reduce the accuracy of GPS receivers, disturbances known as Selective Availability (SA) were introduced into the C/A signal. GPS receivers were able to reduce SA interference. However, these disorders were turned off on May 1, 2000, and remained turned off after September 11, 2001.

The idea of Geometric DOP is to state how errors in the measurement will affect the final state estimation. This can be defined as:

```
GDOP = Δ(Output Location) / Δ(Measured Data)
```

The low DOP value represents a better positional precision due to the wider angular separation between the satellites used to calculate a unit's position. Other factors that can increase the effective DOP are obstructions, such as nearby mountains or buildings.

DOP can be expressed as many separate measurements:

- HDOP – horizontal dilution of precision,
- VDOP – vertical dilution of precision,
- PDOP – position (3D) dilution of precision,
- TDOP – time dilution of precision,
- GDOP – geometric dilution of precision.

Sample EGNOS Dilution Of Precision (HDOP) shows picture above:

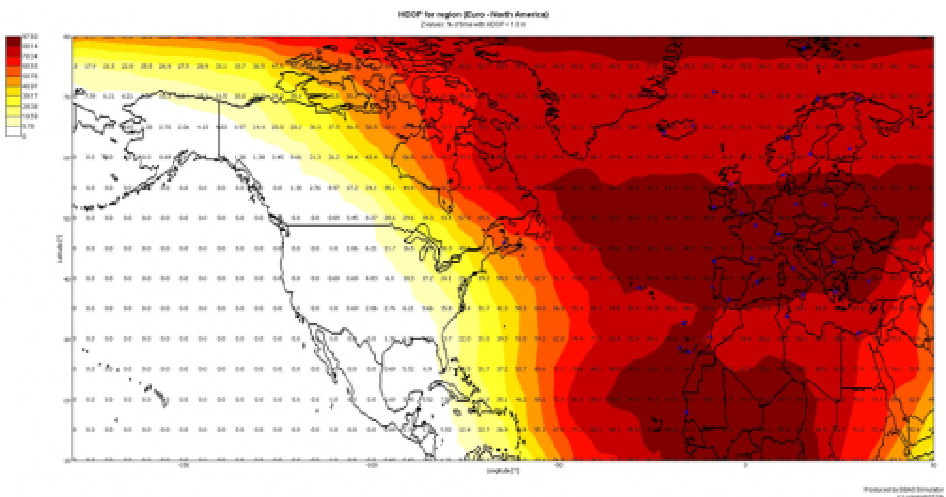


Figure 70. GNSS HDOP

GNSS Ionospheric signal propagation over a region shows another picture above:

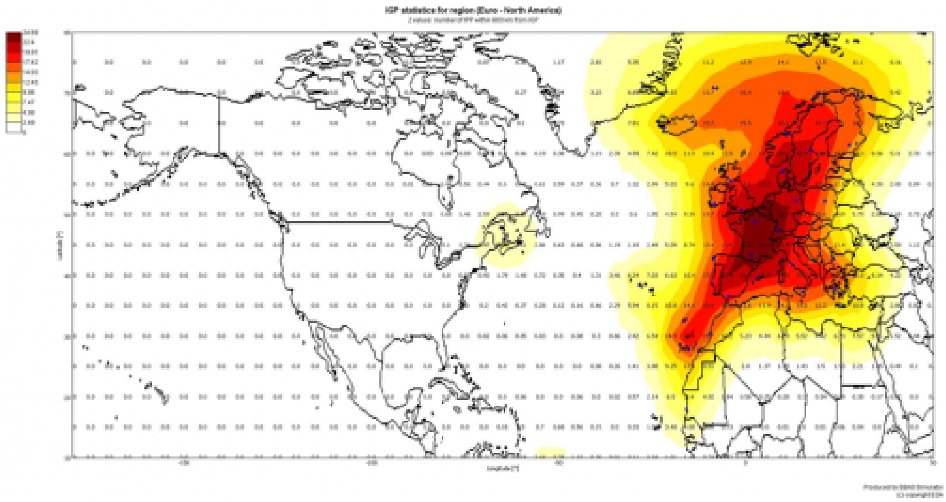


Figure 71. GNSS IONO

10.3.15.1. EDCN Introduction

EGNOS Data Collection Network (EDCN) was created in 2001, to acquire experience but also develop procedures on how to assess and validate the performance provided by augmentation systems like EGNOS. This data collection network is composed of multiple stations hosted often at Universities. It is complemented by the contributions from Air Navigation Service Providers interested on certifying and providing SBAS services in their national air space (among others AENA Spain, DTI/DSNA France, NATS UK, ENAV Italy, NAV Portugal, Skyguide Switzerland, PANSA Poland). All collected data is managed by EUROCONTROL in France, in charge not only of developing all the software used to process the data defined in the avionics standards, but also the definition of procedures and accumulation of results to present them coherently to the Regulator body in charge of the ESSP certification as EGNOS Operator.

10.3.15.1.1. EDCN Components

- GNSS satellite constellations – GPS NAVSTAR, GLONAS, Galileo,
- EGNOS satellites – Inmarsat IOR-W,AOR-E,Artemis
- GNSS ground-mounted receivers (NavTech, Septentrio, etc.)
- PC computers, LAN, WAN – Internet,
- Software – PEGASUS powered by EUROCONTROL,
- Central Database.

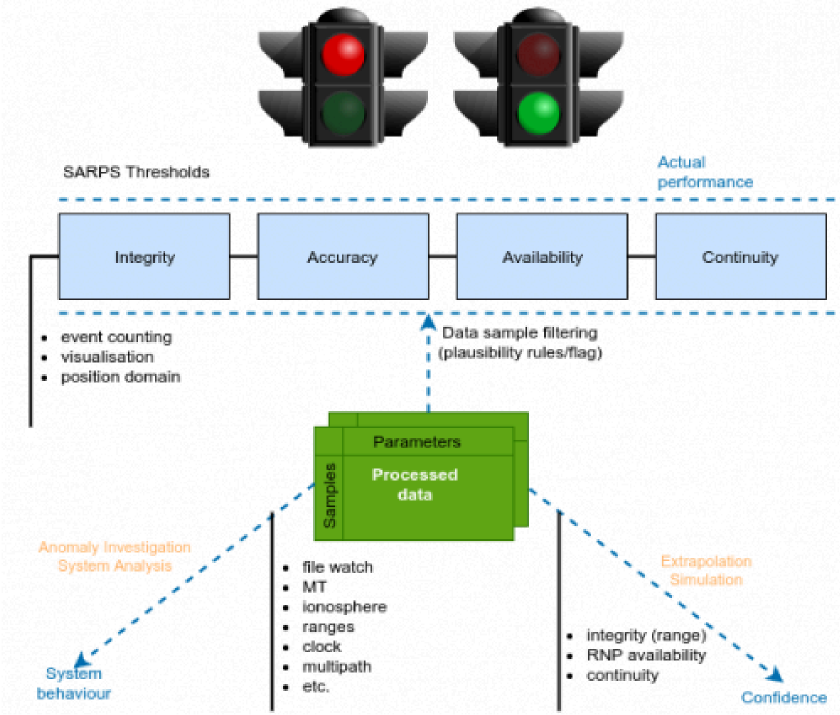


Figure 72. EGNOS monitoring system

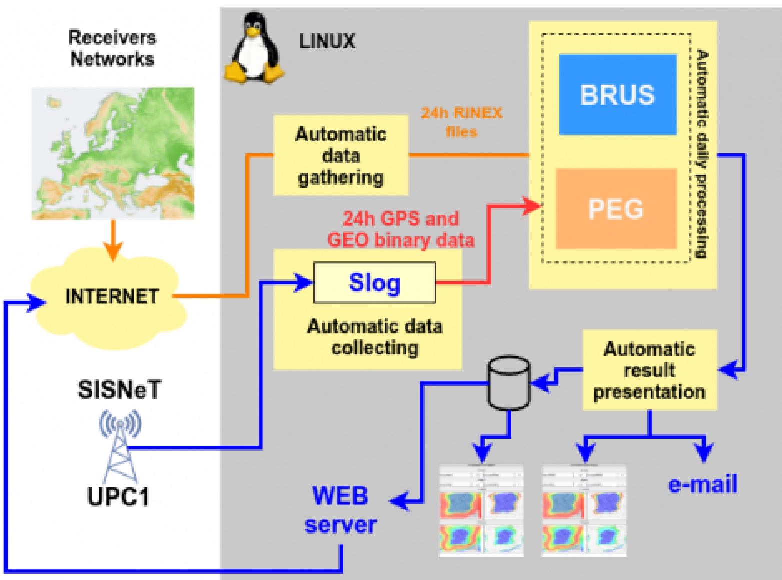
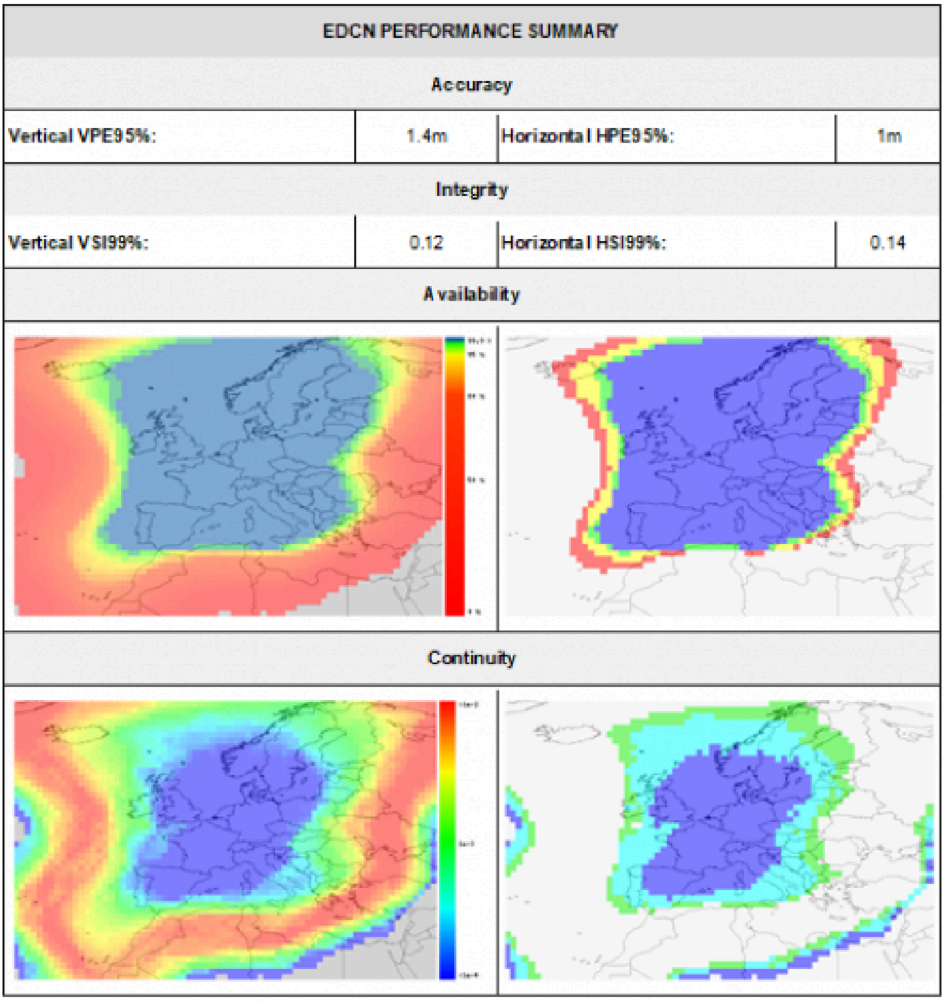


Figure 73. EGNOS architecture diagram

10.3.15.1.2. EGNOS availability maps

- 100% >= Availability >= 99% : blue,
- 99% > Availability >= 98% : green,
- 98% > Availability >= 95% : yellow,
- Availability < 95% : red.



EDCN PERFORMANCE SUMMARY			
Accuracy			
Vertical VPE95%:	1.4m	Horizontal HPE95%:	1m
Integrity			
Vertical VSI99%:	0.12	Horizontal HSI99%:	0.14
Availability			
Continuity			

Figure 74. EGNOS availability

10.3.15.1.3. EGNOS Signal Continuity

Availability EGNOS SIS signal for PRN120 satellite.

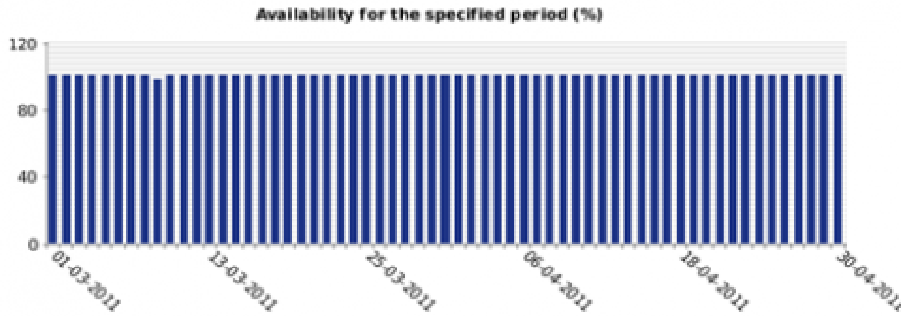


Figure 75. PRN126 signal continuity

There was no SIS broadcast during 23rd and 24th July 2011, for further details see July Performance Report available at ESSP web page

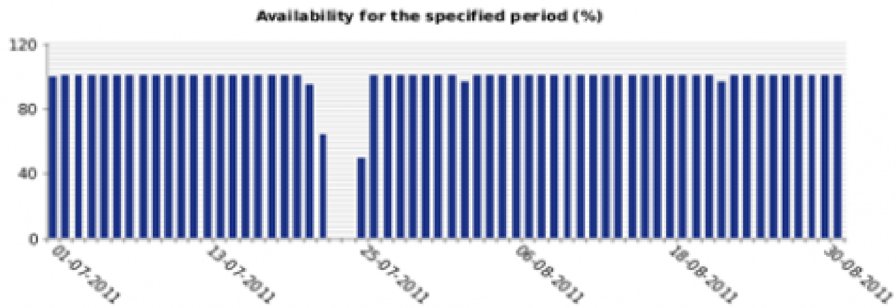


Figure 76. PRN120 signal continuity

10.3.16. GNSS Receiver hardware chips

Autonomous UAV usually rely on a GPS position signal which, combined with inertial measurement unit (IMU) data, provides highly precise information that can be implemented for control purposes. To avoid accidents in an area heavily populated by other UAV or manned vehicles, it is necessary to know exactly where the UAV is located at all times. Equipped with GPS, a UAV can not only provide location and altitude information but necessary vertical and horizontal protection levels. Typical GNSS receivers which can be easily used in the UAV platforms are listed below.

10.3.16.1. Multi-GNSS Receiver Module Model GN-87

GN-8720is a stand-alone, complete GNSS receiver module that can provide accurate GNSS PVT (Position, Velocity & Time) information through the serial communication channel. The key device inside is eRideOPUS 7, the latest monolithic GNSS receiver chip that contains ARM9 processor for signal tracking and processing, high performance integrated LNA, PLL Synthesizer, Down-converter, ADC and DSP. GN-8720 also contains Flash ROM for firmware and data storage, TCXO for reference clock, 32kHz crystal for RTC (Real-time clock), L1 band SAW filter and power-on reset circuit. Main features are as follows:

- Supports GPS, GLONASS, SBAS, QZSSand Galileo;
- Outputs a time pulse (1PPS) synchronized to UTC time;
- Software upgrade capability by Flash ROM;
- Active Anti-jamming capability to suppress effects of CW jammers;
- Multipath mitigation effects;
- Works in both Autonomous mode and Assisted mode;
- GPS/GLONASS high indoor sensitivity;

- Fast TTFF of typically <1 second when in hot and 30seconds in warm and 33 seconds in cold start conditions;
- Available of an active and passive antenna;
- Unordered List ItemLow profile, small SMT package reducing the mounting area and mounting cost.

Figure 77. Multi-GNSS Receiver GN-87 module

10.3.16.2. ACEINNA OpenRTK330L

ACEINNA's OpenRTK330L includes a triple-band RTK/GNSS receiver coupled with redundant inertial sensor arrays to provide cm-level accuracy, enhanced reliability, and superior performance during GNSS outages. The OpenRTK330L integrates a very precise 2 Degree/ Hour IMU to offer ten to thirty seconds of high accuracy localization during full GNSS denial. This enables autonomous system developers to safely deliver highly accurate localization and position capabilities in their vehicles at prices that meet their budgets. OpenRTK330L's embedded Ethernet interface allows easy and direct connection to GNSS correction networks around the world. OpenRTK330L's CAN bus interface allows simple integration into existing vehicle architectures. The multi-band GNSS receiver can monitor all global constellations (GPS, GLONASS, BeiDou, Galileo, QZSS, NAVIC, SBAS) and simultaneously track up to 80 channels. The module has RF and baseband support for the L1, L2, and L5 GPS bands and their international constellation signal equivalents.

Figure 78. ACEINNA OpenRTK330L module

10.3.16.3. BCM47755

The BCM47755 supports two frequencies (L1+L5), achieves lane-level accuracy outdoors and much higher resistance to multipath and reflected signals in urban scenarios, as well as higher interference and jamming immunity. The BCM47755 incorporates numerous technologies that enable ultralow power consumption in both the location function and the sensor hub function. The device features a low-power RF path, a Big/Little CPU configuration composed of an ARM-based 32-bit Cortex-M4F (CM4), an ARM-based Cortex-M0 (CM0), and is built in a 28 nm process. The BCM47755 can simultaneously receive the following signals:

- GPS L1 C/A;
- GLONASS L1;
- BeiDou (BDS) B1;
- QZSS L1;
- Galileo (GAL) E1;
- GPS L5;
- Galileo E5a;
- QZSS L5.

Figure 79. BCM47755 module

10.3.16.4. UBLOX NEO-M9N module

The NEO-M9N module is built on the robust u-Blox M9 GNSS chip, which provides exceptional sensitivity and acquisition times for all L1 GNSS systems. The u-Blox M9 standard precision GNSS platform, which delivers meter-level accuracy, succeeds the well-known u-Blox M8 product range. NEO-M9N supports concurrent reception of four GNSS. The high number of visible satellites enables the receiver to select the best signals. This maximizes the position accuracy, in particular under challenging conditions such as in deep urban canyons. NEO-M9N detects jamming and spoofing events and reports them to the host so that the system can react to such events. Advanced filtering algorithms mitigate the impact of RF interference and jamming, thus enabling the product to operate as intended. A SAW filter combined with an LNA in the RF path is integrated into the NEO-M9N module. This setup allows normal operation even under strong RF interferences, for example, when a cellular modem is co-located with NEO-M9N. NEO-M9N offers backwards pin-to-pin compatibility with previous u-Blox generations, which saves designers time and cost when upgrading their design. Software migration requires little effort thanks to the continuous support of UBX messages across product generations.

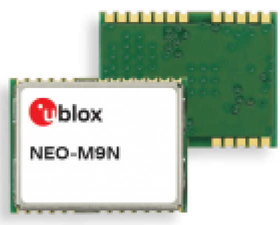


Figure 80. UBLOX NEO-M9N module

10.3.17. UAV designed GNSS Receiver modules

The UAV industry requires lightweight heavy-duty fully IP69K or IP67 waterproof and low power GNSS receiver modules. The sample list of useful UAV GNSS receiver modules which uses different popular GNSS receiver hardware chips are listed below:

10.3.17.1. Radiolink TS100 Mini GPS Module for Mini PIX Flight Controller

The Radiolink TS100 Mini GPS Module for Mini PIX Flight Controller can measure with a 50-centimetre precision of accuracy when working with concurrent GNSS. The prc-lNA low loss circuit design has enhanced ability to capture extremely weak signals. The TS100 can seize very weak signals and effective suppression of input interference at the same time.

Description

- Positioning 20 satellites in 6 seconds at open ground and valley station-keeping ability,
- Reception of GPS/QZSS LI C/A, GLONASS HOf, BelDou Bl SBASIl C/AWAAS, EGNOS, MSAS,
- Radiolink TS100 Mini GPS Module for Mini PIX Flight Controller,
- Features an M8N GPS decoder chip, with u-Blox UBX-M8030 (M8), 72-channel,
- Max update rate: up to 10Hz,
- Compatible with: Radiolink Mini PIX.

Specification

- Positional accuracy: 50-centimeter precision GNSS,
- Velocity precision: 0.1m/s,
- Max height: 50000m,
- Max speed: 515m/s,
- Max acceleration: 4G,
- Max update rate: up to 10Hz.

Sensitivity

- Tracking and Nav.: -167dBm, Reacquisition: -163dBm,
- Cold start: -151dBm, Hot start: -159dBm,
- Time to first fix: Cold start: 26s, Hot start: 1s.

Connect ports

- Power supply: voltage 5VDC+-5 percent, current 50-55mA,

Ports

- GPS UART interface,
- Baud rate: 1.2K/4.8K/9.6K/19.2K/38.4K/57.6K/112.5K,
- Geomagnetic I2C interface.

configuration

- Geomagnetic: QMC5883L which with the same technology as HMC5983 form,
- Antenna: 2.5dbI high gain and selectivity ceramic antenna,
- Double filter: SAWF(Surface acoustic wave filter) form Murata.

Dimensions

- 3.20 cm x 3.00 cm x 1.20 cm / 1.26 inches x 1.18 inches x 0.47 inches,
- Weight: 0.0200 kg.

Figure 81. TS100 Mini GPS Module

10.3.17.2. Here 2 GNSS module for Pixhawk 2.1

Description

- Here 2 GNSS for Pixhawk 2.1,
- Sensitivity: Tracking and Navigation–167 dBm, Hot start–148 dBm, Cold start–157 dBm,
- Active antenna and passive antenna,
- 72-channel u-blox M8N engine GPS/QZSS L1C/A, GLONASSL10F BeiDou B11, etc.,
- Navigation update rate: Max 10Hz.

Specification

- Processor: STM32F302,
- Compass Gyro Accelerometer: ICM20948,
- Barometer: MS5611,
- Receive type: 72-channel u-blox M8N engine GPS/QZSS L1C/A, GLONASSL10F BeiDou B11, Galileo E1B/C SBAS L1 C/A: WAAS, EGNOS, MSAS, GAGAN,
- Navigation update rate: Max 10 Hz,
- Positioning Accuracy: 3D FIX,
- Time to first fix: Cold start 26S, Aided start 2S, Reacquisition 1S,
- Sensitivity: Tracking and Navigation-167dBm, Hot start- 148dBm, Cold start- 157dBm,
- Assisted GNSS: Assist Now GNSS Online, AssistNow GNSS Offline (up to 35 days), AssistNow Autonomous (up to 6 days) OMA SUPL& 3GPP compliant,
- Oscillator: TCXO(NEO-M8N/Q),
- RTC Crystal: Built in,
- ROM: Flash(NEO-M8N),
- Available Antennas: Active antenna and passive antenna,
- Signal Integrity: Signature feature with SHA 256.

Ports

- UART/12C/CAN: JST_GH Main interface, Switch Internally,
- STM32 Main programming interface: JST_SUR.

Dimensions

- 76mm x 76mm x 16.6mm,
- Weight: 49g.

Figure 82. Here 2 GNSS Module

10.3.17.3. Radiolink SE100 GPS Module for PixHawk

Description

- 2.5dbI high gain and selectivity ceramic antenna,
- MMIC BGA715L7 from Infineon power amplify IC,
- SAWF (Surface acoustic wave filter) form Murata,
- HMC5983 from Honeywell geomagnetic.

Specification

- Positional Accuracy: 1 m precision when working with concurrent GNSS, 2.5 m precision when working with single GNSS,
- Velocity precision: 0.1 m/s,
- Max height: 50000 m,
- Max speed: 515 m/s,
- Max acceleration: 4G,
- Max update rate: up to 18 Hz,
- Sensitivity Tracking & Nav.: –167 dBm; Reacquisition:–163 dBm; Cold start:–151 dBm; Hot start:–159 dBm,
- Time to first fix: Cold start: 26 s, Hot start: 1 s,
- Connect ports,
- Power supply: voltage 3.3VDC+-5%, current 50~55 mA.

Ports

- GPS UART interface, baud rate: 1.2K/4.8K/9.6K/19.2K/38.4K/57.6K/112.5K,
- Geomagnetic I2C interface.

Dimensions

- 48.5 mm x 15.3 mm,
- Weight: 34.2 g.

Figure 83. Radiolink SE100 GPS Module

10.3.17.4. UBLOX NEO 6M GPS Module

Description

- Built-in 25 mm x 25 mm x 4 mm high gain ceramic antenna,
- Built-in EEPROM, make sure no data loss,
- Built-in reverse polarity protection,
- Built-in dual-colour LED, a clear indication of GPS status.

Specification

- SuperSense ® Indoor GPS: -162 dBm tracking sensitivity,
- Support SBAS (WAAS, EGNOS, MSAS, GAGAN),
- Max speed: 500 m/s,
- Voltage: 3.3 V–6 V,
- Inner chip UBLOX NEO 6M,
- With EEPROM memory function,
- Baud rate 4800-115200,
- Refresh rate 1.5 Hz,
- Cable length 10 cm,
- Support rod length: 12 cm.

Dimensions

- 22 mm x 30 mm x 4 mm,
- Weight: 12 g,
- Antenna: 25 mm x 25 mm x 7 mm.

Figure 84. UBLOX Neo 6M GPS Module

10.3.18. UAV designed GNSS Receiver external antennas

Some GNSS modules require external satellite antennas to improve positioning and reduce the radio signal disruption in different field conditions. In general, such antennas are designed as omnidirectional, heavy-duty, fully IP69K and IP67 waterproof for use in telematics, transportation, and remote monitoring applications. This antenna delivers 3G/2G antenna technology, and GPS/GLONASS/GALILEO for next-generation high bandwidth telematics navigation systems provides an unobtrusive, robust construction that is durable even in extreme environments.

10.3.18.1. Spartan MA650.ST 2in1 antenna

Specification

- GPS/GLONASS/GALILEO and Cellular 3G/2G,
- GPS/GLONASS/GALILEO – High gain LNA up to 32dB 0.3M RG-174 Fakra Code C Blue Jack,
- Cellular 3G/2G – 850/900/1800/1900/2100MHz 0.3M NFC200 Fakra Code D Jack,
- GSM/GPRS/CDMA/PCS/DCS/UMTS/HSPA,
- Low Profile, Robust and Stylish Design,
- Construction: Heavy Duty, Integrated Metal Base/Ground-Plane,
- No Ground Plane Required,
- Case: IP67 and IP69K – Water Resistant,
- Dimensions: H: 36mm, Ø: 148mm,
- Weight: 570g.

Figure 85. Spartan MA650.ST GPS External Antenna

10.3.18.2. BN-345AJ GNSS antenna

B N-345AJ is a multi-star multi-frequency satellite navigation antenna with high gain, miniaturization, high sensitivity, multi-system compatibility. The bottom of the antenna is magnetized for easy attachment. The antenna is made of UV-resistant PC material and ultrasonic technology. It can be sun-proof, high-temperature resistant and IP67 waterproof.

Specification

- Frequency Range: BDS B1/B2/B3 MHz,
- GNSS Constellations: GPS L1/L2/L5 GLONASS G1/G2 GALILEO E1/E2/E5a/E5b/E6,
- Gain: <5.5 dBi,
- Antenna AR: ≤3.0 dB,
- Phase center error: ±2 mm,
- Polarization: Right-hand circular polarization,
- Port Impedance: 50Ω,
- Antenna size: 76 mm x 72 mm x 27 mm,
- Weight: 175 g,
- Waterproof grade: IP67.

Figure 86. BN-345AJ GNSS antenna

10.3.18.3. BN-244 spiral GNSS antenna

The antenna has the characteristics of small volume, high positioning precision and lightweight. The total weight of the antenna is less than 30g, which is especially suitable for equipment such as an unmanned aerial vehicle (UAV).

Specification

- Frequency Range: GPS L1/L2 MHz,
- GNSS Constellations: GLONASS L1/L2 BDS B1/B2/B3 GALILEO E1/E5b,
- Gain: 3 dBi,
- Antenna AR: ≤3 dB,
- VSWR: ≤1.8,
- Polarization: Right-hand circular polarization,
- Port Impedance: 50 Ω,
- LNA Gain: 33±2 dB,
- Noise figure: ≤1.8 dB,
- Operating voltage: 3.0 V-18.0 V,
- Operating current: ≤42 mA,
- Connector type: SMA-J,
- Antenna size: Φ 27.5 mm x 58 mm,
- Antenna weight: ≤ 30 g.
- Waterproof grade: IP67

Figure 87. BN-244 GNSS antenna

10.3.19. Indoor navigation techniques

In the previous chapter Navigation, there is a presentation of the navigation methods for drones that are flying outdoors and can receive satellite signals. To some extent, satellite-based navigation works indoors but usually with much-lowered accuracy and not in the deep shade from the surrounding walls and ceiling. Moreover, outdoor positioning inaccuracy, i.e. 1 m, does not impact mission to the extent as may indoors.

Indoor positioning requires then different techniques, where some of them need additional infrastructure while others base on the on-board of the drone hardware and algorithms. Usually, it applies to the smaller drones and requires precision positioning in 3D space, even some 1 cm accuracy. There are several techniques available to solve this problem that we present below.

10.3.20. Introduction to the indoor positioning

10.3.20.1. Positioning methods

Among the algorithms used for localization, we can distinguish methods based on the measurement of signal propagation time or measurement of signal strength. Using the signal temporal propagation model, we can use techniques such as:

- AOA (Angle of Arrival) – this method uses the measurement of the angle of the incoming signal from the broadcasting station to approximate the location [31].
- ADOA (Angle Difference of Arrival) – like the AOA method, it is based on calculating the differences of angles of the signal received from the transmitter [32].

Methods that measure the angles can be performed if the receiver is equipped with directional antennas or with a matrix of antennas.

- TOA (Time of Arrival) – with this method the time of arrival of the signal transmitted from the mobile client to the base stations is measured. The distance from each station is calculated by determining the time of arrival of the signal, depending on the speed of wave propagation [33]. The precise synchronization is required in this method.
- TDOA (Time Difference of Arrival) – It is similar to the previous method with one difference; transmitting base stations and receiver do not have to be synchronized with each other. The geometry of this technique is also used in Multirateriation [34].
- TOF (Time of Flight) – it is a technique used to measure distances between several devices.

In a one-way TOF receiver must be precisely synchronized with the transmitter. In TW TOF (Two Way TOF, also known as RTT – Round Trip Transmission) each device has a transmitter and receiver, and the flight time measurement process includes signal exchange and measurement of results between two cooperating units [35]. One of the devices initiates the internal time measurement and sends the message to the responding unit. The answering device sends its measurements - delay from receipt to response. Using both time measurements internal and external, the initiator calculates the distance.

Among the techniques that use signal propagation, we find techniques that use geometric transformations. These are:

- Triangulation – positioning by angle measurement [36]. Using the knowledge of geometry, we can calculate the receiver's location relative to known transmitter positions. Knowing the angles of incoming signals from at least three transmitters, it is possible to determine the position of the receiver.
- Multilateration – also known as hyperbolic navigation, positioning by measuring the distance difference (or time difference of flight) between the receiver and stations placed at known positions. It is also possible to measure the difference of distance from one sending station to two receivers. As a result of measurements, we obtain a hyperbolic curve with a large number of possible positions. To determine the exact position, a second measurement is made, using different sending stations, in which we get another curve intersecting the first in the place that will be the designated position [37].
- Trilateration - positioning by measuring the distance (or time of flight) from signals coming from many transmitters [38]. Knowledge of the angle of incidence of signals is not needed here. Two intersecting circles marked with a signal from transmitters will allow us to determine the position. Due to noise in measurements, at least three transmitters are used in typical applications. GPS system is a hyperbolic navigation system using the TDOF technique but also determines the TOF according to the receiver's clock.

Using the signal strength model, we can use the RSSI (received signal strength indicator) signal in the receiver, which is a measurement of the power present in a received radio signal. It is provided in Bluetooth and Wi-Fi devices. It can be used to determine the distance from the transmitter, but the transmission power fluctuates due to changes in environment, objects movement which results in inaccurate positioning. That’s why the fingerprinting method is the preferred method for positioning.

- Fingerprinting – It assumes measuring the signal strength in the tested room, at measuring points located at a fixed distance from each other (this distance determines the measurement precision), and based on this data, a map of the signal strength in the room is created. The receiving device then measures the signal strength and compares it with the map mentioned above [39].

There are some technologies based on different principles that can be used in indoor positioning systems, including radio waves, image recognition, visible or infrared light, ultrasound, inertial and others. Here we shortly present some of the possible solutions.

10.3.20.1.1. Inertial and Dead reckoning

These systems use inertial sensors (accelerometers, gyroscopes) on the user to estimate relative rather than absolute location, i.e. the change in position since the last update. They require little or no infrastructure to be pre-installed in buildings [40]. This method is based on a previously determined position and known or approximate speed in time. The biggest problem, in this case, is the inaccuracy of the whole process, which increases over time. To counteract this phenomenon, stationary points are used, and error correction techniques are used. **Inertial Navigation System** is a system that tracks position by estimating the full 3D trajectory of the sensor at any given moment. For positioning inside buildings, the most commonly used concept is Pedestrian **Dead Reckoning** [41], the accelerometer built in the smartphone [42] or as the separate device is attached to the body of a moving person and most often counts its steps.

10.3.20.1.2. Ultrasound

The principle of operation of systems based on ultrasonic waves comes down to measuring the difference in the time of arrival (TDOA) of information by the receiver from the transmitters, which are arranged in such a way as to cover the entire surface of the building [43]. Knowing distances from transmitters receiver can calculate the current position using the trilateration algorithm. The receiver Systems based on navigation using ultrasound are strongly dependent on temperature and frequency depending on the Doppler shift.

10.3.20.1.3. Magnetic field

The Earth has its own natural magnetic field. The field intensity can be easily measured anywhere on its surface. Studies have shown that buildings cause changes in magnetic field values [44]. These changes depend on the building materials used during the construction of the building. Due to the fact that these values do not change over time, it is possible to use them to create a map of the building with a specific magnetic field strength at individual points. This allows determining the position after measuring the magnetic field. This solution does not require any additional infrastructure in the building. The magnetometer is available on virtually every smartphone. This issue was addressed by the Finnish company IndoorAtlas [45].

10.3.20.1.4. Light and vision systems

Some systems utilize QR codes as markers placed on the ceiling or walls [46]. A smartphone camera detects and decodes the markers to get the location inside a room. QR code detection and decoding are relatively simple and memory efficient. Each code contains an ID, which delivers enough information to deliver the information required to determine its reference location.

An interesting approach has been proposed by Philips [47]. Its indoor positioning system is based on two, well-known assumptions: every building has to have lights installed, and every LED light flickers with some frequency. This product uses lamps as well known and calibrated reference points. Each of the lamps has a unique (across given venue) ID. This ID is encoded in the form of the frequency of the LED and is invisible to a human eye. Cellular phone’s camera captures signals, and then the phone decodes the LED ID from its frequency and determines the lamp position on the captured frame.

Both systems require that the cellular phone’s camera is pointed to the ceiling what is rather an unnatural position while using the phone.

Positioning systems can also use infrared light. There can be found systems with mobile IR transmitter (beacon) and stationary receivers [48] or stationary light source and mobile IR receiver [49].

The image processing technology is also used to position the user. The challenge to implement such a system is the complexity and resource-intensiveness of the employed algorithms. Running these algorithms on a mobile device is usually not possible and thus has to be offloaded to a server. Another challenge is to recognize structures that are visually very similar such as plain walls which often repeat within buildings [50]. Although there are some examples of image processing implementations this technique seems to be too demanding to be widely used at this moment, however, early solutions that are implemented, i.e. using Intel Movidius processors used in DJI Tello home drones seems to be very promising https://www.intel.com/content/www/us/en/internet-of-things/computer-vision/overview.html.

Optical flow

One of the oldest and most widely spread techniques for 2D flat positioning using vision systems is an Optical Flow. Optical flow positioning uses a similar technique that is present in the optical computer mouse. There is a camera observing surface under the drone, so optical flow technique is most suitable for 2D surface positioning, whereas altitude is controlled with a digital barometer. The principals of this technique are pretty simple: a camera facing downwards is observing any movements of the surface; thus deducing, the drone moves then the opposite way. There are many, ready modules to simplify this operation so nowadays, drone implementors not necessarily implement optical flow algorithm themselves, rather you use ready module that returns horizontal and vertical movement. Of course, integrated solutions (i.e. DJI drones using Movidius processor as a flight controller, i.e. DJI Tello) implement this feature natively, supporting not only the 2D surface but even 3D space, using downwards and forward camera.

Sample module (same used in many computer mouse's) is ADNS3080:

Figure 88. Sample optical flow sensor

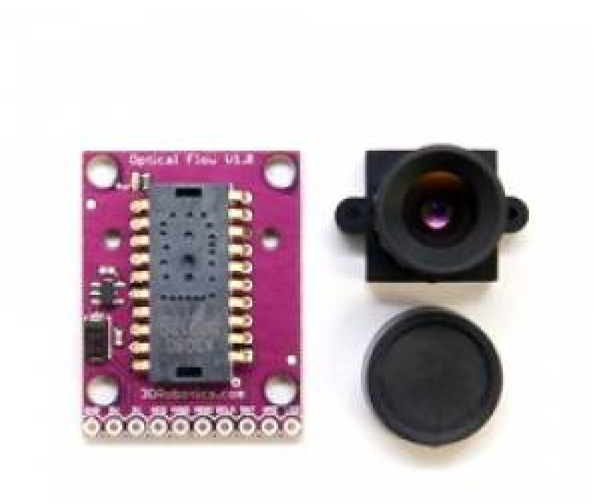


Figure 89. Sample optical flow sensor

Optical flow is easy to integrate, and many flight controllers provide almost “plug and play” support for it. Anyway, they have many serious disadvantages as well:

- Limited range: works best on some centimeters to a couple of meters range. One limitation is fixed optics camera unable to get the sharp image below some distance on the one hand (also drone shadow won't help when hovering close to the surface), and camera's limited resolution when considering high altitude: small changes will remain unnoticeable because of the fixed FOW (Field of View).
- Works best in good light conditions only: as it is a visible range camera used, it works more-less as human eyes do. It won't work correctly in darkness or low ambient light.

- Works only above irregular surfaces. As the camera needs to be able to identify some characteristic points, it won't work over the flat surface as, i.e. glass plane, the same way many PC mouse's won't work.
- When surface moves, the drone will follow it!

It is a pretty common observation, that flying the drone with optical flow enabled over, i.e. grass field covered with leaves during autumn causes the drone to drift with the wind directions as leaves are moving over the grass. Moreover, flying on low altitude generates propeller's airflow stream down hitting the ground, causing the aforementioned leaves to move, thus moving also the drone itself. Be careful and use it as supplementary, not primary technique!

10.3.20.1.5. Radio

Among radio technologies used for localization, the most popular ones are RFID, Bluetooth, and Wi-Fi. New UWB technology has built-in functionality to help to implement the positioning systems.

- RFID - using an RFID system, tags are arranged in a fixed pattern on the floor. Absolute coordinates of the location are stored in each tag to provide the position data to the mobile receiver. An RFID reader reads the data from tags that are under the effective area of RFID antenna [51].
- Bluetooth - there are some systems based on Bluetooth technology. Bluetooth Low Energy beacons are small devices that emit a signal which provides mobile applications with the context that they are running in. Using this information mobile phone can calculate the location of the user knowing where the given beacon is located. Such a system that uses information from one beacon only has rather low precision (10-50m) and can be used for applications where only information about presence in a given place is needed. The system based on this technology has been created by Apple, transmitters in this system are called IBeacon [52]. It is also possible to calculate position using signals from more than one beacon [53]. The mobile device scans for beacons around it and using trilateration determine a more accurate location based on the signal strength (RSSI) from different beacons. Such a solution works pretty well in theory. Still, in the real environment, there are many difficulties like the noise and signal variation what makes it really hard to calculate the position properly.
- WiFi - wireless networks can also be used to locate users [54]. Access points are usually present in buildings with a wireless network. It is possible to use them for localization purposes. Their arrangement is adjusted so that the signal reaches all places in the building where system users can be found. The user's device has the ability to measure the signal strength of all access points within its range. Each of them has its own individual MAC address. In one place, the signal strength from specific access points remains at a similar level. This allows creating a map that specifies the signal strength from specific access points in different locations (fingerprinting). In this way, it is possible to determine the position after measuring the signal strength of the network access points.
- UWB [55] (Ultra Wideband) is a technology intended for wireless digital data transmission over short distances at low power density. The technology occupies a large (greater than 500MHz) bandwidth of the radio frequency spectrum. Wide bandwidth is obtained with the usage of very short radio pulses. It works with limited power, not causing interferences with other radio systems like Wi-Fi and Bluetooth. This technology can be used for high precision indoor positioning. Transmitters are equipped with hardware support to the RTT (Round Trip Transmission) time measurement. This allows measuring the TOF with good precision and using trilateration to calculate the position with centimeter accuracy. UWB seems to be the most promising technology for in-door positioning due to good accuracy, ease of implementation, inexpensive modules, small power consumption and no interferences with other systems.

10.4. UAV Building Components

UAVs share many components with UGVs and Internet of Things. In particular, they use a number of sensors and techniques known from robotics, autonomous cars, sensor networks, sometimes just changing its application. Here we focus on those components that differ from UGV aforementioned in other sections.

10.4.1. Sensors

Sensors deliver to the FC and operator all necessary information about the current state of the UAV. Depending on the airframe used, the purpose of the drone and flight modes available, some of them are optional and some necessary to operate. Most of the flight controllers include at least IMU, frequently magnetometer and pressure sensor. In case they're located as external components, communication is held using popular embedded systems protocols: I2C, SPI and Serial, less often CAN.

10.4.1.1. IMU

IMU is an integrated mems sensor that contains accelerometer and gyroscope. Nowadays IMUs deliver 3D (3 axes) information instead of 1, so it is all integrated into a single chip. Old constructions may contain separated devices, one per axis, but it is almost impossible to find a commercial UAV using this technology.

The IMU is necessary to operate stably any multirotor. A human operator is unable to control multirotor motors directly manually and requires a flight controller (FC) to operate it. FC, on the other hand, requires reference to the current rotation and its acceleration, and that is the purpose, each multirotor drone requires gyros and accelerometers.
IMUs may also integrate barometer and compass (magnetometer) to deliver full orientation to the FC. The common marking is so-called "DOF" (Degree of Freedom) telling exactly, what is integrated within the chip:

- 6 DOF - a basic IMU, usually for racing drones. It is composed of 3 DOF (3 axes) accelerometer + 3 DOF gyroscope, delivering to the drone relative information about its position regarding gravity. This kind of solution, if not assisted with additional sensors, is unable to orientate geographically and unable to hold altitude.
- 7 DOF - an extension to the 6 DOF with a barometer. A common approach is to assembly 6 DOF IMU + external pressure sensor.
- 9 DOF - an extension to the 6 DOF with a magnetometer (compass, also 3 DOF). See remarks on quality in the Magnetometer section, below.
- 10 DOF, a full set integrated (Figure 90). It includes 9 DOF + barometer.

Many FCs integrate IMU (and other chips) onboard. Some use communication protocols and external breakout boards.

Figure 90. Sample 10DOF IMU breakout board

10.4.1.2. Pressure sensors

The barometer is a pressure sensor used to monitor drone flight altitude (vertical position), thus enabling the drone to keep its altitude constant and help the operator to keep them hovering stable. A flight mode where the vertical altitude is kept constant is frequently referenced as "Alt hold" mode, and drones without a pressure sensor do not offer this function. Most of the commercial drones are equipped with at least one pressure sensor; the only exception is racing drones class, where this function is absent or limited and usually disabled during a race if present at all.
The barometric pressure sensor is essential for autonomous operations.

It is easy to find a pressure sensor chip onboard: it has a hole in its fuselage to let the flow of the air inside (Figure 90 upper right corner, silver chip).
Multirotors with this function (alt hold) usually use the controller that the throttle stick neutral position is within its centre, not downwards.
In case of most drones, flight time is less than an hour, and their range is limited to few kilometres, so it is common to assume that air pressure does not change importantly and do not affect altitude calculations over this period and distance/area. For drones that operate for a long-distance/long time, it is necessary to introduce pressure correction systems that will provide the ability to re-calculate altitude, as in case of large scale planes. This is usually done with reference ground stations that deliver current readings and their changes over time and space (i.e. airport or ground station located in the landing area). In lightweight constructions pressure sensor is usually covered with ventilating foam to avoid rapid pressure changes, coming, i.e. from the wind and propellers that may affect UAV vertical stability.

10.4.1.2.1. Relative pressure sensors

Differential pressure sensors are used to check true airspeed. Any flying object's move, in case there is an airflow (wind), can be described by at least two, distinguishable velocities:

- Ground speed, usually obtained from the navigation system such as GNSS (satellite-based) positioning;
- Airspeed, a relative speed within the air.

Above can be equal only if there is no air movements at all (rarely happens). In the case of multirotors, the difference between airspeed and ground speed is not very critical for its operation, while, it can be critical in case of fixed wings. Wind direction drives, in particular, take-off and landing direction of the fixed-wing drones and planes: you always take-off and land towards the direction where the wind blows from, or at least as much as possible, so "against" the wind. It is airspeed that is meaningful when landing, not the ground speed. Meaning can be anything from saving energy to ability to take-off and land at all.

Airspeed is measured using a differential pressure sensor that measures the difference between statical pressure and dynamic one, coming from the pipe located towards the flight direction (Figure ##REF:pitotplane##). This device is usually referenced as Pitot, eventually Prandtl tube and is an essential device in any plane (also its failure historically was the reason for the serious and deadly plane accidents, like Air France flight 447 in 2009). Pitot / Prandtl tubes tend to freeze and block with ice on the higher altitudes, so in full-scale planes, they're usually heated to prevent such accidents (Figure 93). Also, for this reason, this component is usually at least duplicated and located in different locations on the fuselage, sometimes even on the wings.

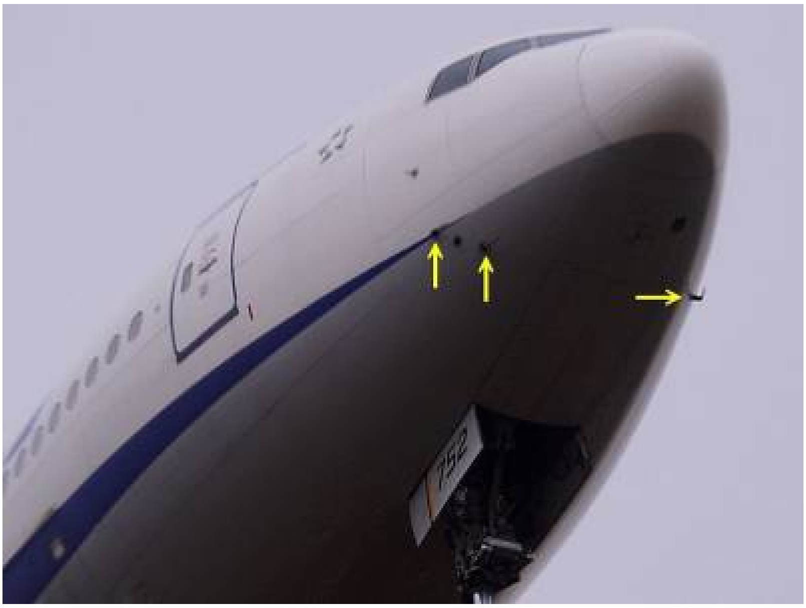


Figure 91. Location of the Prandtl tubes on the fuselage (Boeing 777 aircraft)

Figure 93. Full scale pitot tube with heating system to prevent ice clogs

In the figure 94 there is a Prandtl pipe module for drones, that uses popular MPXV7002DP sensor.

Figure 94. Pitot (Prandtl) tube scale set for fixed wing UAVs

10.4.1.3. Magnetometer

A digital compass is a MEMS sensor able to detect a magnetic field. This enables drones to perform “smart” operation, i.e. to rotate relatively to the magnetic North and keep flight direction. Obviously, this information is also delivered by the satellite navigation systems yet working well for moving objects, while not so precise for a hovering multirotor. Most of the commercial drones include 3 axes (3 DOF) magnetometer. This sensor is very sensitive for the environmental conditions, i.e. indoor building construction, electrical cables, power lines and so on can disturb readings. For this reason, it is pretty common, that operator may require “compass calibration” before the flight. Calibration is as simple as rotating drone horizontal and vertical, to let the FC read maximum and minimum values returned by the magnetometer. The magnetometer can be integrated with IMU or can be a separate module and usually communicates with FC using I2C or SPI protocols. Note, magnetometer (as well as IMU) is physically oriented, so it is common that the breakout board contains markings presenting chip orientation and thus axes (Figure 95).

Figure 95. 3 axes magnetometer module

10.4.1.4. Thermometer

The purpose of using a thermometer in case of drones is threefold:

- Environment monitoring to react for specific flight conditions, i.e. enable de-icing (i.e. Pitot tube heating) or warn operator about dangerous conditions - that usually happens on high altitude flights or in low temperature and high humidity and is related to the dew point;
- Monitoring of internal components state, mostly to avoid overheating and related electronics and battery failure;
- Using thermometer as a part of the mission target, i.e. temperature scan or payload monitoring, etc.

The digital thermometers on the low-level hardware are based on NTCs and PTCs; however, the most frequent case is to use sensors integrated with other sensors like, i.e. barometers are frequently accompanied with a thermometer to ensure temperature compensation, but on can read temperature separately, as well. There are thermometers integrated with microcontrollers as well.

10.4.1.5. GNSS

Satellite navigation is in no doubt a choice number one in drones while flying outdoors. It is for both autonomous flight as well as for remote control ones, even for experienced operators. GNSS positioning can keep drone horizontally stable and thus, i.e. compensate wind drift.
We discuss navigation principals in a separate chapter, here just focusing on its sensors. So far, the only drones that do not benefit from GNSS positioning are FPV racing drones, but still many of them contain receiver to hold their position in other flight modes than racing.

GNSS receiver requires an external antenna (usually ceramic), and because of the signal suppression, it is common to keep the connection between antenna and receiver as short as possible. For this reason, receiver and antenna are frequently in the form of a single block and located in the upper part of the fuselage. The connection between GNSS receiver and FC is usually a serial, pretty frequent one-directional. As GNSS receiver requires an Almanac data to operate, and this one can be received from the satellites (long time) or from the web (short time), some receivers can obtain it from the FC. And it is pretty frequent that FC obtains it from the ground station via telemetry/communication link or directly, i.e. via the cellular connection or other Internet connection available. As downloading an Almanac is time-consuming and it has a direct impact on "getting a fix" on a cold start delay, some receivers contain a coin battery and battery-backup memory, to keep an Almanac ready and not to download it on each cold start (i.e. when main drone battery is replaced).

Nowadays most of the modern GNSS receivers are multi-channel and multi-constellation ones. It means that they use different satellite constellations to obtain position and can benefit from a statistical approach to get even better and more accurate positioning. Additionally, some of the receivers can use WAAS (Wide Area Augmentation System) and SBAS (Satellite Based Augmentation System) to introduce corrections live; both transferred via satellites as well as via ground radio stations. In most cases, the basic constellation used it is GPS (GPS Navstar). In general, the majority of GNSS receivers use at least one more of the following list:

- Glonass (Russia),
- BeiDou (China),
- Gallileo (EU).

A leader of GNSS receivers in drones is Ublox, and you will find their receivers in many amateur and commercial solutions. Advanced models with high precision positioning offer centimetre accuracy (according to the manufacturer) as, i.e. in NEO-D9S series. Standard precision receivers offer some 1m accuracy (static), i.e. popular NEO M8 series (Figure 96).

Figure 96. A GPS receiver module with ceramic antenna

10.4.1.6. Voltage and current sensors

As the majority of the drone power sources are electrical batteries, it is essential to monitor their capacity and use. Typical Li-Po battery has known discharge curve, and one of the most useful sensors is to observe battery voltage and this way predict necessity to terminate mission and land to re-charge or swap the power source. The other approach is to use a current sensor to estimate power consumption and calculate its total use. In practice, both techniques are used as power source down usually equals instant fall of the drone to the ground.

10.4.1.7. Other sensors

A wast number of different sensors, measuring physical phenomena is present in drones. I.e. drones with fossil fuel engines (motors) may benefit from liquid fuel level sensor, measuring remaining fuel capacity, rotation sensor can be used to monitor rotation speed and so on.

10.4.2. Actuators

There are no UAVs without a single actuator. Any device moving around controllable way usually requires at least one actuator per single degree of freedom (usually much more). In terms of drones, we usually talk about servos and motors.

10.4.2.01. A matter of thrust

In many constructions, where motor and propeller attached is primary (or the only) source of lift generated, it is important to use appropriate propulsion, able to deliver thrust necessary for operation. It is not so simple in case of fixed-wings but pretty straightforward in case of helicopters and multirotors: total thrust is a sum of the thrust of all propulsion.
A general rule of thumb says that in any case, thrust to MTOM (maximum take-off mass) should be at least 2:1. The lower the ratio, the less responsible the drone is and in particular if it falls below 1:1, UAV is unable to ascend and to hover. On the other hand, too high ratio causes the drone to be hard to control and may lead to instability.
A typical drone for aerial photography has thrust to MTOM ratio around 3:1 and 4:1.
A racing drone is at least 5:1, and it is not unusual to see 13:1 and more for advanced 3D pilots.

10.4.2.1. Servos

Servos (short from servomotor) are used for various utilities, like, i.e. driving control surfaces, retracting landing gear, changing propeller's angle and many, many more. There is a vast number of different sizes of servos, starting from miniature ones, weighting grams to large ones with some couple of kilograms of its weight. Still, in any case, servo contains an electric motor inside and a decoder able to provide a current rotation angle (note for 360-degree servos, below). It also contains some electronics to control and correct its rotation. Summarising, controlling servo is as simple as “telling” the servo to rotate to the desired angle, and it does it for you, including corrections, if the external force (i.e. pendulum) causes to overshot or undershot the target. A miniature servo is present in figure 97.

Figure 97. Miniature servomotor

Servos are connected with 3 cables, power (+/-) and control. The last one uses PWM (Pulse Width Modulation) to control the angle of the servo. PWM frequency is constant, but it is the duty cycle, that controls the servo rotation. We distinguish 2 types of servos: analogue (standard) and digital. In any case, they're controlled with PWM signal, the difference is PWM frequency and its probing, thus (theoretically) responsiveness. There are also special "slow" servos used, i.e. to deploy flaps and thus change wing's lift force slowly rather than rapidly. A 0-degree rotation angle is equivalent to the minimum duty cycle (see communication section for details) while 180 degrees is for the maximum duty cycle. The duty cycle is standardised, but some manufacturers (i.e. for servos that are operating in the different angle range than 0..180) use special duty cycle values. Refer to the documentation.

Note, many servos marked as 360-degree ones, are not servomotors indeed: they're just motors with gear and do not provide position control, even if their enclosure mimics classical servos. The following set of parameters typically describes a servo:

- Physical dimensions and weight;
- Power voltage range.
- Gear material: plastic/metal, number of teeth and shaft parameters (i.e. diameter, fixing screw and other);
- Torque (kg/cm), frequently provided as related to the powering voltage, it is a maximum mass your servo can lift using 1 cm arm;
- Digital / Analogue;
- Speed measured as the time necessary to rotate servo by 60 degrees under full load. It is also related to the power voltage;
- Others.

There are two most common colour coding for servo cables:

- Futaba: black/red/white: (-GND/+power/control signal);
- Hitec: black/red/yellow: (-GND/+power/control signal);
- JR Radios: brown/red/orange: (-GND/+power/control signal).

In most cases, the plug is a female 2.54, 3 pole connector, JR standard or Futaba. The difference is Futaba connector contains, additionally, side plastic guide, so it is impossible to connect the servo wrong way.

Historically, early RC planes were transmitting PWM signal from the controller (ground segment, user), coded for FM transmission and transmitted to the receiver (onboard, air unit) where it was decoded and then directly to the servos. Because of it, receivers offered one channel and servos were directly connected to the RC receiver, so in fact receivers where offering separate PWM channels, one per each actuator.
You may also find servos with 5 connectors: 2 of them are driving DC motor inside, while 3 others are connected to the potentiometer (decoder) that you can read current rotation angle. This kind of servos requires external control logic, however.

10.4.2.2. Electric DC Motors

Electric DC motors and in particular their lightweight versions are most common propulsion systems in UAVs.
There are two classes of electric motors:

- brushed,
- brushless.

Electric DC motors vary in diameter from a couple of mm to 15cm with a power consumption of some mA to 200A.

10.4.2.2.1. Brushed DC motors

Brushed motors use an internal switching system to the alternate current direction, thus changing magnetic field. It is pretty easy to recognize the brushed motor as it has just two wires (brushless has three). Speed can be controlled via control of the energy delivered, i.e. changing voltage (directly or rather via PWM duty cycle). Brushed, coreless motors are designed to rotate in one direction. This is the reason why brushed motors are marked CW (Clock-wise) and CCW (Counter-wise). While some of them can operate other direction, it is not very efficient. Because brushed motors use the brushed switch inside, named commutator, that uses friction, it wears out over time thus brushed DC motors popular only in smallest, miniature drones. Brushed motor construction is not scalable in terms above some diameter; weight to torque ratio is rapidly decreasing. Because of the mechanical, friction-based, commutator construction, brushed DC motors used to be considered less reliable than brushless ones. The advantage is simplicity on powering and speed control, usually using a single MOS-FET transistor and PWM.
Miniature DC brushed motors are marked pretty frequently with their external sizes: i.e. 8520 means 8.5mm diameter, 2cm length. A common maximum voltage is 1s (up to 4.2V) on most of the miniature drone brushed DC motors. While some report motors can operate on higher voltage (even 2S that is equal to 8.4V max), they tend to overheat then and break quickly. Sample brushed motor is present in Figure 98.

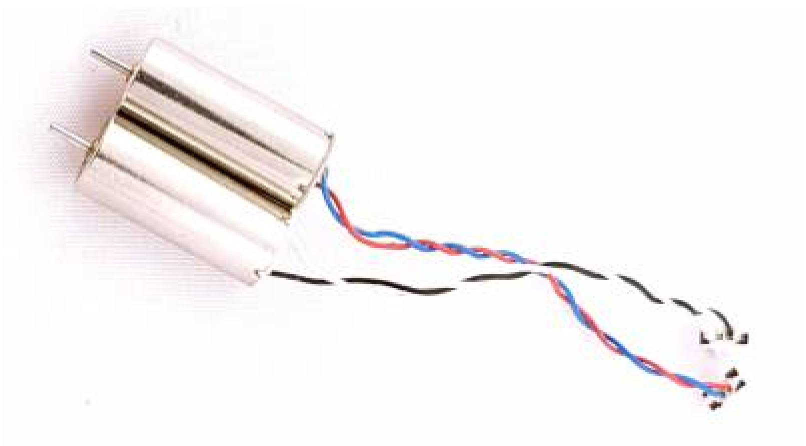


Figure 98. Brushed DC motors (pair, CW and CCW) for miniature quadcopter

Note, CW and CCW motors are distinguishable with cable colours: CW is usually red+blue while CCW is white+black (as in Figure 98). There is no official standard, however.

There is a class of brushed motors for UGVs that are much bigger and support higher voltage, but we do not consider them in drone's section.

10.4.2.2.2. Brushless motors

Brushless motors used to be designed for not so small drones, as their internal construction is pretty complex. Recently, however, brushless motors range was extended with miniature, and super-miniature motors along with assembling technology development and they tend to replace brushed motors even in miniature UAVs. Still, they are more expensive comparing to brushed motors and require complex control electronics (ESC, Electronic Speed Controller). Brushless motors can operate in both directions. Brushless motors connect with 3 cables to the ESC. Changing rotation direction is as simple as swapping two of three wires (any pair).

Some of the medium size brushless motors are marked as CW and CCW. This is not because of their inability to rotate, but rather to prevent self-loosening of the propeller mounted.
Brushless motors do not contain commutator that wears out over time: they are more reliable and lasting longer than brushed ones.

Brushless motor is composed of the stator with coils, connected permanently to the wired terminals and rotating rotor with permanent magnets (Figure 99).

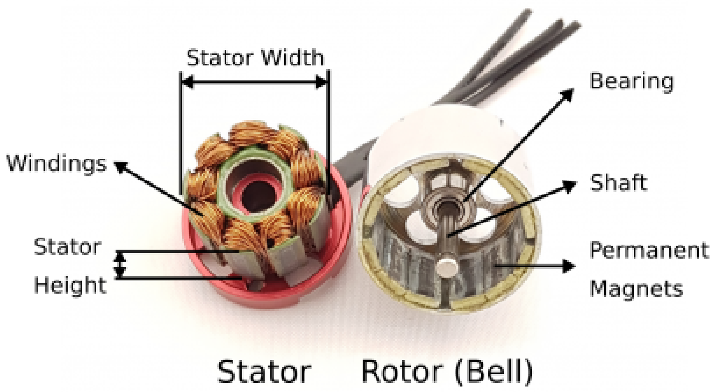


Figure 99: Sample brushless, outrunner motor interior

Universal (non-proprietary) motors have usually marked the way one can read its features, i.e. HK-4015-1450KV means the motor is:

- HK - manufacturer marking (here HobbyKing),
- 40 - motor diameter,
- 15 - motor height,
- 1450KV - 1450 rotations per 1 Volt (see remark below).

Motor's electrical features are defined via maximum voltage it can handle, maximum current and most of all, its rotation speed given as the number of revolutions per 1 Volt of power. Increasing voltage (within maximum limit given) speeds up the motor. This is usually rated under no-load (without propeller) so may differ in real-world scenarios. A rule of thumb is higher KV, faster the motor rotates. It does not necessarily mean it is more energy-efficient, as faster rotation is usually for smaller motors; thus, it delivers lower torque.

Motor's minimum and maximum voltage is usually provided not within the Volt but rather as a number of “S”. Meaning of 1S is explained better in drone's power section, but here please assume that 1S may vary between 3.3V (minimum) and 4.2V (maximum), 3.7V on average.
Some motors also contain a note on its internal, electromagnetic construction, i.e. 12N14P means:

- 12N number of permanent magnets in the stator,
- 14P number of coils in the rotor.

In general, the lower the N and P are, the more powerful engine is, but on the other hand, higher N and P means smoother and more precise rotation (i.e. necessary for gimbals). Typical for multirotor is 12N14P.

The number of permanent magnets in the stator is always multiplied of 3 because the three-phase controller controls it.
The number of coils has to be different than the number of permanent magnets!
Motor's windings (cable diameter and wiring) has a direct impact on its resistance, thus on motor's KV. In short, the thicker and shorter the cable (fewer turns), the lower resistance, the more KV the motor has.
The winding (wiring) can be single strained and multi strained (wired using single or parallel cables, where the parallel is usually three).
Single strained wiring tends to have better heat management thus are used for higher voltage, i.e. 5-6S. Because of the bigger diameter, you cannot pack it very well; thus single strained motors are bigger than multi-strained ones.
Multi strained wiring can be better packed because of smaller empty spaces between wires; thus such coil creates a higher magnetic field than single strained wiring, that means multi strained motors are more energy-efficient and smaller.

Wiring construction neatness is important here because messy wiring disturbs magnetic field generation and lowers overall performance.
Physical properties of the motor include also:

- Maximum thrust (eventually a list of thrust generated, regarding voltage and propeller size/ type).
- Weight.

There are types of mechanical constructions:

- Inrunner: The external body (can like) is static while the rotor is inside of the motor. There is a shaft and construction mimics brushed motors. In such construction, the rotor is called the core.
- Outrunner: The stator with coils is inside while the rotor with magnets is outside: most of the engine is rotating, including external housing. In such construction, the rotor is called the motor bell.

Each construction has some features comparing inrunner to outrunner. In particular, the following is to consider when juxtaposing features of comparable two:

- Inrunner has a smaller diameter than outrunner;
- Outrunner has a lower profile (height) than inrunner;
- Outrunner body rotates;
- Inrunner has better heat dispersion (coils are located outside, magnets inside) than outrunner (this is partially true, cause modern outrunner's shell is constructed like a kind of fan, to ventilate interior);
- Outrunner generates larger torque than inrunner;
- Inrunner has higher KV (rotations per volt) than outrunner;
- Inrunner has better energy efficiency.

In the table below, there are proposed applications with respect to the inrunner and outrunner motors (Table 3).

Table 3. Inrunner and Outrunner applications

Inrunner	Outrunner
racer fixed-wing, EDF, RC Car, RC Boat	multirotor, helicopter, RC airplane (for 3D evolution), gimbal

In the Table 4 there is a juxtaposition of a UAV quadcopter frames and corresponding motors and propellers. One may use them as a starting point when planning new construction.

Table 4. A proposal for quadcopter frame size, corresponding propeller and motor

Frame Size	Propeller Size	Motor Diameter	KV Range
?15cm	?3in	11xx↔13xx	>=3000KV
18cm	4in	18xx↔2204	2600↔3000KV
21cm	5in	2205↔2306	2300↔2600KV
25cm	6in	(2206-2208)↔2306 or taller	2000↔2300KV
35cm	7in	25xx	1200↔1600KV
45cm	8-11in	26xx and larger	800↔1200KV
90-100cm	13-20in	4114↔6010	320↔450KV

Please note, it is very individual to construct a drone, so above values are on average.

10.4.2.3. ESC

The ESC (Electronic Speed Controller) is necessary to control a three-phase brushless motor, so we discuss them in this section.

ESC accepts power input usually directly from the drone battery, and there is one ESC per motor (Figure 100). Its purpose is to control brushless motor rotation speed and also direction. ESC is controlled using one of the RC protocols directly from the RC receiver or (most common as for now) indirectly from the FC. Various protocols include bi-directional ones, but in any case, the output of the ESC is simply three wires that drive directly brushless motor. It is ESC's duty to generate an appropriate sequence to let the motor spin correctly.

Figure 100. ESC

The major features of ESC are:

- input voltage range (provided in “S”),
- maximum current,
- size and mass,
- communication protocol used (most ESCs can handle at least a bunch of them, including simplest PWM signal),
- set of additional features, like, i.e. ability to deliver stabilised power to the flight controller or RC receiver (so-called built-in BEC),
- programmability.

Regarding brushless motor, ESC is not only responsible for speed control but also for speed-up / slow-down characteristics, behaviour on zero throttles (if the motor is kept in position or let it float freely) and so on. As ESC generates PWM on its outputs, its frequency impacts motor torque, temperature and smoothness of rotation. Some ESCs deliver capability to force constant rotation speed (useful for variable pitch propellers), and most of them offer programmable change of the rotation direction (without need to swap wiring that may cause re-soldering).

Programming (changing of the parameters/features/behaviour) of the ESCs is possible threefold (depending on particular model and manufacturer):

- via so-called programming cards - they have nothing to do with cards; actually, it is simply an external device you connect an ESC to and choose a configuration that is then stored in the non-volatile memory of the microcontroller that manages ESC;
- via a sequence of the input signal changes (operator using throttle enables programming mode and then in sequence changes all parameters);
- via FC or PC computer - some of the ESCs provide programming input, usually serial or USB, while others let the FC program it.

In the communication section, we discuss ESC communication protocols.

In the case of miniature drones and also FPV in class 250 or smaller, as total energy consumption is rather low or average, it is common to see 4 in 1 (for quadcopters) or 6 in 1 (for hexacopters) integrated ESCs that you connect motors directly to a single board. It is only a physical construction, integrating separate ESCs into the single board to minimise space. Some of them are in the form of a stack (along with flight controller and other communication modules), usually mounted at the bottom of the stack.

10.4.2.4. Piston Engines

Piston engines are miniature versions of the motors as we use in full-size cars and planes. In the case of RC scale, they are usually single-piston ones (Figure 101). Still, some constructions mimic radial engines (Figure ##REF:rcradialengine##) as we know them from 1st and 2nd world war warplanes (radial engine was invented in 1901, however).
It is not very common to see piston engine in multirotors, because of their construction complexity, weight and control challenges. Rather, they take their place in scale UAVs in the form of fixed-wing ones and larger construction, usually exceeding some 25kg.

Figure 101. Single piston RC engine

Figure 102. Radial RC engine

There are two common types of power type, regarding fuel they use:

- gas - similar like in case of passenger cars, using a spark plug to ignite fuel. Those use regular, eventually high octane aviation fuel,
- glow with glow plug that uses heat from compression of the methanol fuel along with the heat of the glow plug.

For construction simplicity, scale engines are air-cooled.

10.4.2.5. Jet engines

Indeed there are scale jet engines, turbo-jets in fact, so far there are no turbo-fan constructions available. Those engines are used in top of high speed and high-performance UAVs and require complex construction (Figure 103). There are used mostly in fixed-wing drones as a replacement for propeller-based propulsion and due to the high cost and complex maintenance, are not very popular. Yet drones using those engines are the ones that hold records for speed of their flight, reaching 700km/h.
Interestingly, in 2019 there was a first successful presentation of a jet quad drone that uses 4 jet engines, instead of propellers.

Figure 103. Scale jet engine

10.4.2.6. EDFs

EDFs are not a class of propulsion themselves, but we mention them here as they mimic turbofan engines that are not represented in UAV class so far. EDFs have nothing common with real turbofan engines other than the way they look from outside (Figure 104). The need for this construction came from the need to mimic passenger plane engines that are turbofans (as, i.e. in popular Boeing 737 or Airbus A320). EDF is short from Electric Duct Flow and uses electric inrunner motor, mounted coaxially, that spins the large ventilator which generates the thrust.

Figure 104. EDF motor

10.4.2.7. Propellers

Along with motors, propellers are the most notable component of most (all but soarers) UAVs. Propeller's cross-section looks like wing's cross-section, and it used to generate lift or thrust (eventually both). Depending on the drone purpose, its size, motors used, one need to choose appropriate propeller type, size and material to ensure performance, efficiency and safety. Popular UAV propellers can be as small as one inch of diameter and as big as some 40 inches. The material used to construct propeller is wood, plastic (mostly nylon and polycarbonate), carbon fibre (Figure ##REF:prcpropeller##). Each propeller has at least 2 blades that can be fixed or rotating parallel to its length (so-called variable pitch propeller).

Figure 105. Sample quadcopter propeller set of four (CW+CCW)

Each propeller is characterised with the following set of parameters:

- diameter;
- rotation direction (CW/CCW);
- a number of blades (typical is 2 to 5);
- fixed/variable pitch;
- pitch;
- hub diameter (shaft diameter, sometime delivered with a set of adapters);
- material;
- foldability.

Choosing an appropriate propeller is state of the art: first of all, in most cases, a first-hand choice is provided by the motor manufacturer. Note, the higher the diameter, and the higher the pitch, there is a bigger load to the motor; thus, it also means higher current. And higher current impacts directly ESC and battery, not to overstress both. When using ready UAV, the choice is usually a replacement 1:1 as delivered by the UAV manufacturer. When designing your own drone, there is a variety of choices, and usually, the motor manufacturer delivers a parameter table where propeller sizes are juxtaposed along with expected construction (rated under full load).

In the case of multirotors, each pair of motors rotate opposite, so propellers are usually sold in sets (pair, 4 pieces), as CW + CCW.

Most of the propellers have their elementary data printed on their hub or close to it. Markings are provided in inches, so, i.e. 1045 means 10 inches of the diameter and 4.5 inches of pitch.

10.4.2.7.1. Propeller's pitch

What exactly is propeller's pitch? It is the theoretical distance the propeller would move in a solid environment during one full turn. You can consider it as in case of a screw going through the wood. Obviously, the higher the pitch, the bigger force it generates but similar way to the wing, if pitch it to high, laminar flow may break and thus lower the performance. The higher the pitch, the more torque it requires to operate; thus, the motor load is bigger.

10.4.2.7.2. Propeller balancing

The bigger the propeller is in its size, the more important it is to keep it balanced. Vibrations disturb IMU and cause bearings and shafts to wear out quicker. Serious vibration may lead to airframe destruction. Balancing is done using propeller balancer device (Figure 106).

To change propeller weight (balance it) you may use a piece of self adhesible thin tape (to add weight) or use water paper to polish the blade to remove weight. In no case should you modify the upper part of the blade, but bottom one.

Never modify (add, polish) the top part of the blade - that will affect negatively laminar airflow and will cause lower propeller performance.
If propeller seems to be cracked, worn out, broken or jagged, do not let the UAV fly in this condition. Such propeller should be replaced unconditionally. It is also reasonable to change propellers after any crash even if blades and hub seem not to be affected at all.

Figure 106. Propeller balancer device

10.4.2.7.3. Foldable propellers

In many constructions, propellers are foldable. Popular DJI Mavic series use foldable propellers to decrease drone size in transportation. Propellers are folded on the operation planar (Figure 107). Once motors spin, blades unfold because of the centrifugal force.

Figure 107. Planar foldable propellers, for transportation, DJI Mavic Mini

In the case of motorized soarers (fixed-wing UAVs that benefit from energy-less soaring over the sky), however, fixed pitch propellers would cause resistance, dramatically lowering soaring performance. In such a case, we use foldable propellers as present in Figure 108. Propellers unwind automatically, once motor spins and flow of the air force them to fold over fuselage when not in use, to limit air resistance. There are two versions of such propellers for motors located in the front of the aircraft (so-called pullers) and those that fold outwards when using a motor located in the back of the flying wing airframe (so-called pushers).

Figure 108. Foldable propeller, over fuselage

10.4.3. Flight Controllers

Flight controllers (FCs) are necessary to implement flight logic and in particular autonomous flight. Their features vary from a simple quadcopter stability control to advanced autonomous navigation with collision avoidance using sensor fusion with visual data. Obviously, features are limited with hardware capabilities of the microcontroller used to implement FC, but in case of most modern microcontrollers are equipped with decent core and large memory. The whole logic is based on the firmware used.

There are three approaches to the FCs and firmware:

- closed model - where FC is bound to a particular drone model and cannot be re-configured or adapted to the other airframes;
- open but proprietary - where one can use proprietary FC and firmware (i.e. DJI), but along with aerial part, there is a configuration tool that enables you to fine-tune or even adapt FC to your needs;
- open source - virtually [56], you can reprogram the FC as you wish, up to its hardware limits.

Here we focus on the third approach, and we present a list of most popular firmware available. A time ago, first open-source FC hardware was developed as a natural extension of Arduino (ATMega) microcontrollers. 8-bit ATMegas, as pretty good for early UAVs, mostly fixed-wing ones, nowadays wouldn't handle increasing demand on advanced features for modern operations. There is still support for one of the first available solutions named Ardupilot (actually, its 8-bit version) but the project is considered to be obsolete and rather frozen.

Multicopters required much more powerful microcontrollers to use IMU and RTOS (Real-Time Operating System) to handle flight logic. Thus the most popular microcontrollers include Arm core-based ones, in particular, low power, low voltage 32-bit STM32 family.

The general schema of the drone with FC as a heart of it is present in Figure 109. Most of FCs include a variety of extension ports with serial, I2C, SPI and CAN protocols. Some of them have integrated RF module to communicate with selected remote controllers and telemetry systems directly. Some also offer image processing and video overlay features, i.e. for FPV racing.

The most popular microcontrollers for FCs are:

- Historically, ATMega 2560 (Ardupilot, 8 bit);
- STM32 F1, F3, F4, F7 - in no doubt, the most popular at the moment: most of the open-source and proprietary FC use one of those chips. STM32 is 32 bit one. The first choice for FPV racing, video filming drones, and so on;

- Broadcom BCM series with ARM core, not so low-power, well known from Raspberry Pi (and clones). Rather for larger drones, with some at least 45cm body;
- Intel Movidius, a niche yet very powerful microcontroller, capable, i.e. to implement live video stream processing for optical stabilisation. Implemented in Ryze/DJI Tello;
- LPC1768 with ARM core, also niche but used by DJI (i.e. Naza M);
- Intel Atom, x86 and x64 architectures - for large drones.

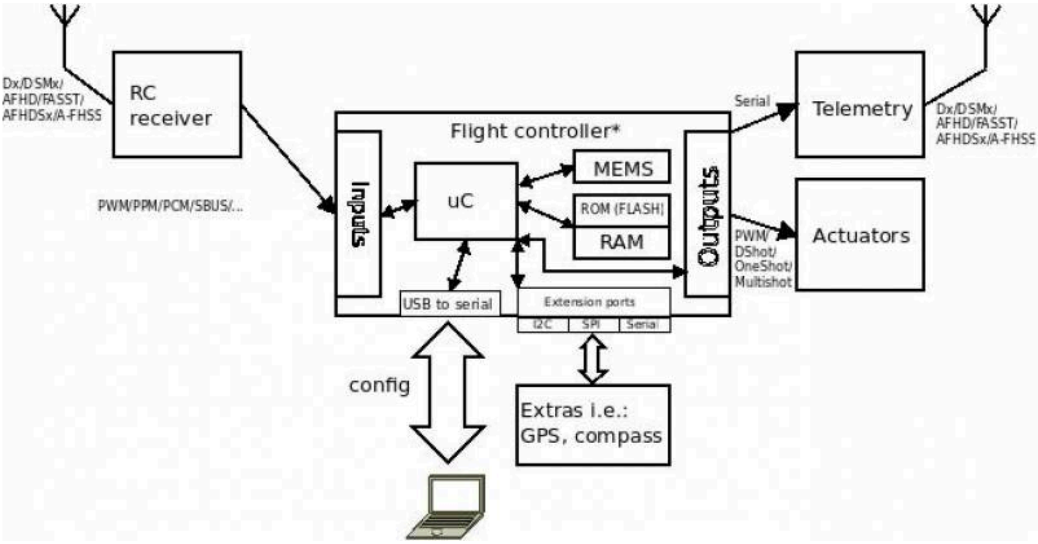


Figure 109. Flight Controller diagram

Some FC boards integrate programming circuit, voltage stabilisers and even brushed speed controllers (usually in the form of MOS-FET transistors), i.e. F3 EVO brushed for miniature drones (Figure 110). FC usually integrates at least 6DOF IMU (usually more DOF), and more complex and more expensive constructions include barometer and accelerometer on-board. STM32 is powerful enough to decode most of the RC protocols in real-time (parallel to other duties), so there is no need to use an external decoder, just the high-frequency radio to extract a digital signal from FM transmission.

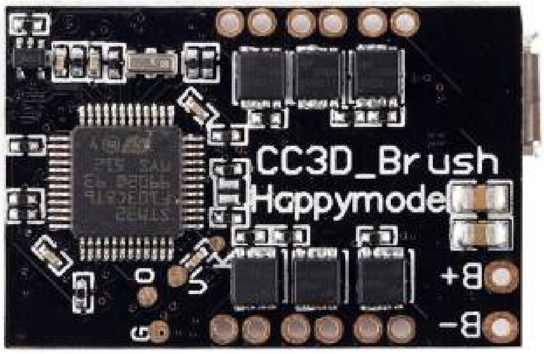


Figure 110. Sample brushed, STM32F3 (STM32F303CCT6) integrated flight controller, weights 3g only!

Some RC protocols use inverted logic. While most of STM32Fx can invert signal on the GPIO inputs so can handle it with ease, STM32F4 cannot, so several decoded protocols is electrically limited. It is not a problem in case you use an external RC receiver, but in case of miniature drones, adding any additional PCB dramatically increases its weight.
Many manufacturers deliver “stackable” flight controllers for 25cm and bigger drones class. One of the boards (usually mounted as second from the bottom) is FC itself, while the bottom board is usually integrated speed controller (brushed or brushless). Optionally, the top board is an extension board, i.e. handling on-screen display overlays for FPV racing, GPS receiver, and so on (Figure 111).

Figure 111. Stacked FC, here Kakute Holybro with brushless ESC for quadcopter

An interesting initiative is Pixhawk, open standard hardware for drones [57]. This project originated from the Ardupilot, and at the moment constitutes de-facto standardisation in professional drones. Pixhawk and its clones implemented according to the open standard are available from various vendors and use common software solution that includes FC firmware, ground station software and other components (Figure 112). This initiative integrates much well-known hardware and software companies, including 3D Robotics, Microsoft, Yuneec, Flir and NXP (among others). DJI is not a member of this consortium, however.

Figure 112. Pixhawk FC, open standard implementation

10.4.3.1. Firmware Review

FC hardware is nothing without the firmware that implements various features. Open source FC firmware is available via Github (in most cases), and is extended daily, and periodical deploys. Everyone can download repository, and “cook” its own version of the firmware. As there are many different hardware solutions even for same microcontrollers, most of the repositories contain “config” files for a compilation, that prepares binary firmware packages for specific boards. Construction of this firmware on the code level is modular, so, i.e. it is easy to disable (remove) SD card logging function if your board does not provide one or you're not willing to use it, and you need to free resources for other modules.

10.4.3.2. Open Source

Here we present a list of common FC firmware:

- Ardupilot - historically the oldest one and also the most popular even nowadays (currently for 32-bit microcontrollers, formerly for 8-bit microcontrollers). For UAV and also for UGV. Provides wide autonomous flight features including ground station software and telemetry.

A bunch of related projects (non-exhaustive) that originate from one source (former OpenPilot [58]):

- Cleanflight - stable, changing slowly, new release once a quarter.
- Betaflight (a fork of the Cleanflight) - Development area for CleanFlight. If you have most modern hardware, look for firmware here (CleanFlight may be delayed). Updates appear weekly.
- Baseflight - also related to the above, but currently outdated, do not use if not necessary. Provides firmware for some old, resource-limited FCs.
- INav (a fork of the Cleanflight) - oriented for autonomous flights and video filming.
- Raceflight (a clone of CleanFlight) - racing drones and performance-oriented. Lacks such features like, i.e. GPS navigation.

- PX4 Flight Stack - similar to Ardupilot - firmware for open hardware initiative (i.e. Pixhawk FC).
- LibrePilot (a clone of former OpenPilot), niche. You can find it in many cheap CC3D (STM32F3) FCs.

Updating of the firmware may be tricky, as requires connecting FC in bootloader mode via USB cable. Note, as firmware changes the way it stores parameters from version to version, it is pretty common that re-flashing cleans your configuration and requires you to configure controller from scratch (i.e. PID parameters, additional sensors, and so on). Always do a backup and configuration snapshot before updating firmware.

10.4.3.3. Proprietary

DJI offers a series of large FCs, designed for professional utilities, as, i.e. A3 FC. While the solution is closed and proprietary, due to the large adaptivity capabilities, many people decide to use it, mostly because of high quality and legend reliability. In fact, the firmware is upgradeable, but there is no access to the source code. Along with FC there comes a configuration software that let you adapt controller features for your specific needs and your airframe.

10.4.4. Remote Control Systems

RC control is a must for the majority of drones. Whether it is a fully manual flight or just remote monitoring and ability to take over in case of unforeseen situation, RC connection should be reliable. Even most advanced military UAVs present ability to let the human operator take manual control.
The remote control can be considered as controlling directly actuators remote way using radio communication from the ground controller (Transmitter) to the aerial unit (Receiver), and this is the way early RC models were implemented. For simplicity, the aerial unit delivered PWM signal directly, able to control servomotor, without a need to translate it. Nowadays, RC communication is usually bi-directional, where control signals are sent from the RC ground Transmitter to the aerial unit Receiver, while telemetry data is sent opposite. Sometime telemetry data is sent via separate channel and hardware; sometimes it is integrated with the Transmitter-Receiver combo solution. In any case, we consider a Transmitter to have many "channels" where one channel is equivalent to control one remote actuator. Basic channels drive control surfaces (for fixed wings) or indirectly motors via FC, and those are throttle, rudder, aileron and elevator (as in fixed wings). Eventually, similar control applies to multirotors and helicopters. By the main channels, there are auxiliary ones, used for various operations: camera gimbal control, gear retracing, flaps control and so on.

10.4.4.1. Controllers

Ground RC controller uses two sticks (to operate basic channels) whether it is a physical device or, i.e. a touch screen of the mobile phone or tablet. Some RC controllers contain built-in LCD display (Figure 113), while others use phone or tablet (Figure 114), or are "bare" style, without any observable controls, that is a case for FPV racing, where the operator wears FPV glasses (Figure 115).

Figure 113. RC controller with mobile phone for monitoring and configuration

Figure 114. RC controller with mobile phone for monitoring and configuration

Figure 115. RC controller for FPV racing

Ground controller is using one of the assignments of control sticks called “modes”. The most popular is Mode 2, where left stick operates the throttle and rudder (yaw) while the right stick controls elevator (pitch) and ailerons (roll) (Figure 117).

While Mode 2 seems to be most popular, it is very individual. The second most popular is mode 1 (Figure 116) but there are also modes 3 (Figure 118) and 4 (Figure 119), barely used.

Figure 116. RC Mode 1

Figure 117. RC Mode 2

Figure 118. RC Mode 3

Figure 119. RC Mode 4

The modern approach used in drone construction assumes that user interface (RC controller) should be separated from the transmitter to let the user decide, which radio standard to use in their scenario. For this reason, there is a vast number of RC controllers that have exchangeable transmitters. While this approach causes some more work while implementing the solution, ability to use one controller to exchangeably control many drones sound interesting because operators simply "used to" use a particular device.

Modes presented in Figures 116, 117, 118 and 119 define four, basic channel, necessary to control a drone. More channels are usually bound to the switches, and even if transmission resolution is somehow linear (i.e. mapped to the range 0..1023 in the receiver), binary switches usually send two values: 0 or max. There are also potentiometers and three-position switches (i.e. to deploy flaps to pre-defined positions), sliders and +- switches, changing channel value up and down. They're usually located on the top of the RC controller, eventually at the back to let the operator use fingers to access it easily (Figure 120). Channels bound to those control switches are usually referenced as AUX and numbered starting with 5 and up.

Figure 120. Additional switches (located on the figure close to the antennas) that control AUX channels 5+

Modern RC controllers use a microcontroller and can mix channels as necessary: i.e. flying wing requires mixing of aileron and elevator, while the rudder is not in use at all.

Channel mixing can be done with FC or on the ground RC controller.
Microprocessor-based RC controllers are usually able to freely bound UI components with channels, even with complex scenarios, where, i.e. full throttle can set some other channel to trigger booster in the jet engine to provide additional thrust. For this reason, RC controllers provide a menu to configure its parameters and bind UI controls to channels. It is also common that "out-of-the-box" linear characteristic of the main channels can be altered, i.e. to sigmoidal or limited once some maximum deflection of the control sticks has been reached. It provides an easy way to change drone responsiveness or limit its parameters for, i.e. inexperienced operator.

10.4.4.2. Transmitters and Receivers

RC Transmitter is a radio section connected to the RC controller (or eventually ground station, i.e. PC computer, mobile phone and any other device dedicated for remote control of the UAV). The majority of the RC solutions are incompatible between manufacturers, and within the manufacturers, there are incompatible series as well. It is common to buy a Transmitter+Receiver combo (Figure 121). Eventually, when the Transmitter is physically integrated with the Controller, there used to be delivered Transmitter+Controller+Receiver. It is worthful to mention that many series are backwards compatible, but, i.e. provide a limited number of features (i.e. lower number of channels transmitted or a one-, instead of a two-directional transmission, and some standards last for decades even if considered obsolete.

Figure 121. Transmitter module and 8 channel Receiver combo for universal Controllers (DJT standard)

Transmitter and Receiver both have to be "bound".\\Binding brings the possibility to own only one transmitter and many receivers (for many UAVs) obviously controlling one at a time.
Nowadays, binding fixes communication between particular devices using digital IDs, but historically analogue system required both radios had exchangeable "quartz" (oscillators) thus enabling multiple operators to operate only their drone even if sharing common space and fix it via setting same frequency. Naturally, two operators sharing the same frequency were causing interference and usually lack of communication, leading to broken connections (and possibly crashes). It is no longer a case, as digital transmission and frequency hopping used by many manufacturers, enables multiple operators to share the same radio space, obviously within reasonable limits.

Modern Transmitters and Receivers are two-directional ones:

- uplink: transmit commands from ground Transmitter (Controller, Ground Station) to the air Receiver,
- downlink: transmits in the reverse direction than uplink, sending telemetry data.

Two directional transmissions have great features, not to mention, it is possible to forecast "out of range" as Receiver transmits at least RSSI (Received Signal Strength Indicator) presenting current connection quality.

The most important features defining Transmitter and Receiver capabilities are listed below:

- a number of channels: at least 4, usually 6 or more;
- one-directional or two-directional communication;
- radio frequency and modulation / protocol / standard used;
- connector standards and size for Transmitter (i.e. compatibility with particular series of Controllers when considering universal modules);
- Receiver's size and weight (important for small and miniature drones);
- antenna connector standards;
- Receiver's telemetry ports and other communication ports;
- Receiver's output protocol (see communication protocols between Receiver and FC);
- other.

10.4.4.3. Ground Control Stations and Telemetry

By the manual Controller and Transmitter-Receiver channel, professional solutions (but also amateur ones) use Ground Stations. They are in the form of PC/Mac computer and dedicated software, eventually using Android/IOS mobile or tablet.

Sometimes ground station and software is integrated with RC Controller, as, i.e. in case of Yuneec

ST 16 (Figure 122). This is the proprietary and closed solution.

Figure 122. Integrated Ground Station with Controller (Yuneec ST16)

Open source solutions for Ground Station (software) related to the ArduPilot ecosystem, and include (among others):

- Mission Planner (Figure 123),
- APM Planner,
- MAVProxy,
- QGroundControl,
- Tower (DroidPlanner),
- many other.

Figure 123. Mission Planner open source Ground Station software

There are proprietary solutions that correspond with open source hardware and firmware, thanks to the open MAVlink protocol (see communication section).

10.4.5. Video

Video cameras play an important role in UAVs ecosystem, in particular in the aerial section (UAV itself).
Their purpose is a dual one:

- used to implement main task (purpose) of the drone device, i.e. aerial photography and video recording (perhaps the most common use), surveillance, monitoring, inspection and photogrammetry;
- flight monitoring and control, in the particular image based stabilisation, FPV flights, autonomous and manual navigation;

In any case, it requires a vast number of different cameras, lenses, mounting methods and wireless transmission solutions.

10.4.5.1. Cameras

Drone cameras vary in size and optical capabilities. While some 480p camera is pretty enough for FPV racing, it is useless in case of professional cinematography, where 8k cameras are required, following user's demand on video quality.
For professional filming, drones used to be equipped with more than one camera. Amateur solutions share one, eventually two cameras, between UAV operator and camera operator (movie maker). In most cases and amateur solutions, UAV operator and camera operator is a single person.
Drone manufacturer can deliver aerial photography cameras or, if UAV's MTOM is huge enough, they can carry professional movie-making equipment, DSLR camera and so on (Figure 124).
Some manufacturers offer an interchangeable range of cameras, including video cameras, multispectral ones and thermal, sometimes integrating them in one body (Figure 125). Those are used in thermal inspections but also in SAR (Search and Rescue) activities.
In any case, the camera has to be stabilised, and it is desired it can rotate (pan, tilt) in any direction, drone independent. For this reason, there are gimbals: they provide the ability to stabilise the camera and keep filming direction stable, even if drone rolls, pans or yaws, due to the manoeuvring or, i.e. windy conditions and vibrations coming from the propulsion system. Obviously, we consider here mostly multirotor airframes, but it also applies to the fixed-wing and helicopters. Majority of the movie recording drones are multirotors, however. Fixed wings ones are used when there is a need to record on long distance / long flight time and availability od such drones is rather limited - they are more popular in military solutions as reconnaissance and surveillance UAVs.

FPV systems, on the other hand, are least demanding in terms of optics, quality and peripherals. They are usually analogue ones because analogue transmission is almost zero latency and low video latency is essential for performance racing flights. For this reason, cheap CMOS and TTL cameras are used, delivering 480 / 575 lines, usually interlaced. Recently there started to appear digital FPV systems that introduced new video quality (i.e. 720p) with low latency (low as 28-30ms as, i.e. DJI FPV system). As it is good enough for beginner racers, professionals still use analogue systems as unbeatable at the moment. It is also pretty common that FPV cameras transmit low-quality signal (analogue or digital) to the FPV operator, but locally record high-quality video stream to the flash memory (usually microSD card) with at least 720p and even 1080p or 4K resolution (camera depending). The purpose is for a presentation and post-factum conflict resolution that may appear during racing and cannot be noticed in low-quality analogue transmission.

Depth cameras, i.e. Intel Realsense, are used to detect obstacles and avoid collisions with them. Many drones introduce these features now to help the operator. Such cameras are usually front-facing, but recently, there appear new solutions capable of processing multiple video streams onboard in real-time (as, i.e. Nvidia Jetson Nano and Intel Movidius), so new UAVs have cameras facing backwards, down and even to the sides, to deliver 360-degree protection sphere around the drone. Additionally, depth cameras along with regular ones can provide position stabilisation when GNSS or other systems are unavailable, i.e. in case of indoor flying.

Stabilisation cameras provide the ability to keep drone horizontally in one place, thanks to the optical stabilisation and image processing. It can be as simple as using sensors known from optical mouses that obviously have many limitations and as complex as advanced image processing with the detection of the characteristic objects and feature extraction like corners, lines and similar. The modern image processing also delivers the ability to let drones perform optical-based SLAM: Simultaneous Location And Mapping, generating 3D environment scene ad-hoc while flying. Obviously, it is rather for larger drones as requires additional energy thus larger battery, however, i.e. miniature brushed drone DJI Tello, successfully uses front and down-facing cameras for indoor stabilisation (Figures 126 and 127) - the integrated image processing and flight control is implemented using Intel Movidius Myriad chipset. Optical stabilization requires an adequate level of light.

Figure 124. Heavy lifting cinematic drone with professional movie camera onboard (photo courtesy BHPhotoVideo.com)

Figure 125. Dual camera with infrared and video (photo courtesy Yuneec.com)

Figure 126. DJI Tello front camera

Figure 127. DJI Tello down-facing camera

10.4.5.2. Mounting

A good gimbal solution can stabilise in 6 DOF (3 rotation axes + 3 planar movements) and professional and semi-professional drones have the gimbal with a camera hanging under their fuselage (Figure 128). Cheaper solutions offer cameras that cannot yaw because they are mounted in front of the drone: this is in case of the popular DJI Mavic series (Figure 129); still, there is a stabilising gimbal and ability at least to tilt in some limited angles. Some proprietary camera solutions sold with drones introduce the ability to zoom, but the majority of drones provide a wide lens: some 70-120 degrees FOV (Field of View). In case of heavy lifting cinematic drones, all parameters are camera dependent, but it is important to mention, that usually with such gimbal (or drone) there is delivered a set of extra motors and servos, that need to be attached to the camera, to remotely operate it (i.e. rotate zoom ring on the lens or press the photo button), as many cameras do not provide a remote wired/wireless interface to control it. FPV cameras in racing drones do not require gimbals at all. They are fixed to the drone body, usually pointing some 20-40 degrees up, as most of the flight time drone is tilted (Figure 130). The faster the drone is, the bigger is the tilt angle.

Figure 128. 3 axis gimbal with camera integated

Figure 129. Front-mounted camera with stabiliser and possibility to tilt it

Figure 130. FPV racing drone camera, no stabilisation

10.4.5.3. Transmission

Transmission of the video signal between an aerial unit and a ground station is strictly related to the protocols used. We discuss it more in the communication section, but here it is just to mention that video transmission requires wide bandwidth. Obviously, in the case of digital transmission, compression may help to fit into the available bandwidth with a cost of quality. In general, we distinguish two types of transmission:

- analogue, almost zero latency, used mostly in FPV racing;
- digital, using coding and decoding, thus introducing notifiable latency that disqualifies it from the FPV and real-time tasks.

Mixed models include recording of the high-quality video in the aerial unit and transmission via downlink lower quality stream. As there do exist professional video links that let you broadcast high-resolution video stream live (i.e. for live reporting on TV), it is rare to use them in amateur and semi-professional drones as they are heavy units, that require large drones and also cost a fortune. This kind of downlinks use multi-channel transmission and usually operate on licenced radio frequencies, to avoid interference, so requires special equipment.

I case of the amateur and semi-professional solutions, transmission channels operate on popular, “free” radio frequencies and in most countries transmitter power is limited by law. Note, there

are different frequencies in different countries, i.e. North America can freely use 915 MHz. At the same time, it is forbidden to use in Europe as overlaps with cell-phone bands, and opposite, 868MHz is an open frequency in Europe, that is limited in the USA. For this reason, some solutions and hardware may work only locally, and their use can be prohibited in other regions. Many manufacturers deliver EU and US versions of their devices.
Anyway, the most popular frequency for video transmission is WiFi, open 2.4GHz and most of all, 5.8 GHz. Note, even 2.4GHz WiFi has slightly different regulations regarding bandwidth in different countries, but the core remains common for the whole world. The majority of amateur and semi-professional solutions operate on 5.8 GHz, i.e. popular Boscam system (Figure 131). It is also pretty common that cameras transmit data simply via WiFi: you bind a device to the drone camera separate link from RC and receive video stream on a computer, mobile phone, or tablet. In case of analogue transmission, the standards refer to the analogue TV, and it is PAL and NTSC. In the case of digital ones, it is usually a MPEG stream, and resolution is limited to some 720p. Miniature indoor drones use simply WiFi for both control and video transmission, eventually Bluetooth that additionally limits image quality.

Using WiFi and 2.4GHz for video transmission causes frequent video quality glitches in radio-noisy environments, so flight range is drastically limited in such areas.

Figure 131. Analogue 5.8GHz video link

10.4.5.3.1. Antennas considerations

Good antennas in both transmitter and receiver is worth more than extra transmission power. As drone (transmitter) changes its position against ground station (receiver), we usually use omnidirectional antennas for transmission (Figure 132). For long-range video downlinks, there are directional antennas that automatically point towards the drone, based on ground station and drone position.

Figure 132. A set of omnidirectional antennas

On the Figure 132 the antenna to the left is 4 lobes (4 leaves) one, and the one to the right is 3 lobes. 3 lobes antenna is more efficient for transmitting so we put it in the drone, while 4 lobes antenna has higher sensitivity, so it is used for the receiver in the ground section.
Every antenna is intended to work with some particular frequency (or its limited range). Note, using inappropriate antennas drastically limits transmission range! To increase transmission quality and range, it is much better to use antennas with higher gain and suitable for the frequency, than increase power transmission while using the wrong one.

10.4.5.4. Monitors and FPV googles

There are three approaches to present live video transmission:

- external monitors (popular in professional aerial cinematography),
- FPV googles used for racing (Figure 133),
- presentation on the mobile/tablet/dedicated device, separate or integrated with the controller,for the operator (Figure 134).

The last one is the most popular and used in the majority of amateur, professional and semi-professional drones. Obviously, image quality is limited, to some maximum 720p, eventually 1080p. As live transmission is used for monitoring mostly, it is common that cameras mounted on the drone record high-quality video stream.

FPV goggles use 2D vision even if theoretically their construction would allow 3D stereoscopic presentation.

Figure 133. DJI FPV googles for analogue and digital transmission

Figure 134. A controller with mobile phone for video prsentation

10.4.6. Auxiliary

By the aforementioned, there is some additional components, accompanying drone ecosystem, i.e. antennas and trackers, mechanical components, power distribution boards, batteries (we discuss them in depth in another chapter) and so on.

10.5. Power sources specific for UAV

Here we present drone specific energy sources. As mentioned in the components section, there are combustion and even jet engines, here we focus on electrical energy sources, in short, batteries. Drone batteries are connected directly to the ESCs and through them drive motors as most of the current is flowing this way.

10.5.1. Lithium-Polymer batteries

Lithium-Polymer (in short LiPo) batteries are base for powering both drones and ground stations. Their popularity is because of the energy density they present the best energy to weight ratio, so far. It is the most important factor in case of aerial units.

LiPo batteries are composed of cells, that can be used as single ones, connected in serial (common) and parallel (rare). A single cell marking is "1S". A single cell voltage is on average 3.7V, while fully charged, reaches 4.2V, and in any case, should not be discharged below 3.0V on normal use. LiPo batteries are very fragile and overcharging usually finishes with fire and explosion. Discharging below 3.3V causes increased battery wear out, 3.0V is critical, breaking its internal structure, and may cause inability to re-charge it or lead to fire and explosion while recharging. For this reason, LiPo batteries should be under instant monitoring. When treated with care, they last for years of uninterrupted power delivery. You may expect some maximum 3-5 years lifetime.

If the battery is broken (i.e. due to the ground hit of the drone), you can observe cracks, bends or it is swollen, do not use it, discharge fully and recycle.
Never discharge LiPo battery below 3.0V on normal use
LiPo batteries are very fragile and overcharging usually finishes with fire and explosion.
Do not store LiPo batteries fully charged. They should be stored semi-charged with some 3.7-3.8V per cell
LiPo batteries have a known and predictable discharge curve. It means monitoring their voltage tells you how much energy is left inside. Observe discharge curve on Figure 135).

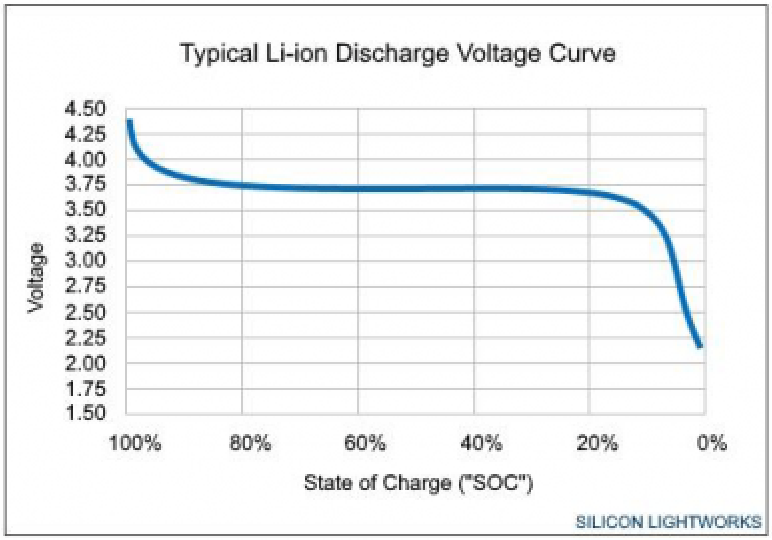


Figure 135. Theoretical LiPo discharge curve, chart courtesy [59]

Discharged to 3.3V is considered to be a situation where immediate battery replacement or recharging is necessary, as then voltage starts to rapidly (non-linear) fall. Note, it is advisable to issue warning earlier as there is usually some time needed for UAV to return to the launch location and safely land that also requires energy.

LiPo batteries present increasing internal resistance for a cell, over time. It is an important factor because it helps to monitor battery ageing and it affects discharge curve as observed from external, user's point of view: the older the battery is, and the bigger the internal resistance is, the earlier the low-voltage warning should be issued (for higher voltage) to ensure safety zone. Following considerations present some typical battery parameters, and it becomes clear what is an impact of the internal resistance.

10.5.1.1. LiPo battery packs

LiPo battery packs are stacks of cells interconnected inside with two major (power) cables for charging and discharging, and several smaller ones used to “balance” particular cells during charge.

10.5.1.1.1. Voltage

Typical LiPo pack is composed of more than one cell, and they are connected in serial (rarely in parallel). Cell construction is marked and usually observable as LiPo pack is just a stacked number of single cells, interconnected internally. Typical marking, i.e. 3S tells there are 3 cells connected in serial, thus increasing total voltage.

Nominal single cell voltage is 3.7V (4.2V max), so:

- 2S ↔ 7.2V (8.4V max);
- 3S ↔ 11.1V (12.6V max);
- 4S ↔ 14.8V (16.8V max).

and so on.

4S1P tells us there are 4 cells in serial and 1S2P tells there are 2 cells in parallel. Theoretically, any combination is possible, but parallel constructions are rare as it is problematic to charge them when there is a major difference in internal resistance.

Depending on the drone size, the number of cells (and batteries) grow: miniature drones use 1S, some 10-15cm ones use 2S, 250 class racers use 3-4S, and video filming drones use 4S-5S. There are bigger constructions, even up to some 10S and more in case of heavy lifter UAVs.

Theoretically, connecting two battery packs in parallel causes increased capacity (sum of two). It should not be done, however, as if both batteries present different voltage, rapid flow from the one charged more to the one charged less (virtually limited only by internal resistance and wires resistance) might lead to overheating, fire and explosion. Additionally, this kind of connection causes a high demand for huge cables, delivering high current via one wires pair.
To increase drone battery capacity and current delivery, it is rather implemented using several battery packs, where each one drives some lower number of ESCs (and motors), and they work virtually in parallel. It requires advanced voltage monitoring of more than one battery pack. Obviously, they share common ground. This kind of solution is common when current consumption of all motors exceeds even most powerful batteries and popular in large drones (i.e. DJI M600).

10.5.1.1.2. Capacity

Each battery has some designed capacity. It changes over time but in any case, there are two types of markings of the designed capacity: using mAh and using Ah units. 850 means measurement is done in mAh (Figure 136), while i.e. 2.2 tells it is 2200mAh = 2.2Ah (Figure 137).

Figure 136. Sample 850 mAh 3S1P, 75C LiPo battery pack

Figure 137. Sample 2.2Ah (2200 mAh) 3S1P, 35C-45C LiPo battery pack

10.5.1.2. Discharging

One of the major factors is the maximum current, the battery can deliver. There are usually two values: constant maximum current and burst one (burst is considered to last couple of seconds, i.e. on take-off). The maximum current is given in "C" number (multiplier of battery capacity). As on Figure 137, the maximum constant current provided is 35C, and burst is 45C that means, maximum constant current in A is:

```
2.2 (battery capacity in A) * 35 = 77A
```

While maximum burst current in A is:

```
2.2 * 45 = 99A
```

Never exceed battery's maximum discharge current. If done so, the battery will overheat, burn and start a fire or even blow.
Motor, propeller and other components impact power consumption and current drawn from the battery. Changing one of them may cause power system re-design need. Remember to check if your battery is still sufficient when upgrading drone with new motors, ESCs or even propellers.

10.5.1.3. Charging

Battery charging requires a smart charger, that can balance battery during charge, to ensure energy delivered via main connectors is equally distributed among all cells. This is a reason we use two sets of plugs when charging a battery: main plugs, delivering a majority of the current, and smaller connector for balancing. Sample connection schema for 5S battery charging is present in Figure 138. The high charging current is delivered to the battery via two main wires, red and black. Green wires connecting battery and balancer are to ensure equivalent voltage distribution, not to overcharge one cell because of undercharging the other: the reason for this situation to happen are differences in the internal resistance of the cells that is natural.

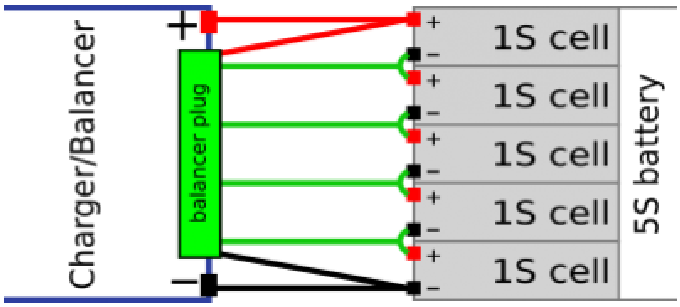


Figure 138. 5S charging connection schematics

Universal chargers (Figure 139) can charge a variety of different types of batteries and also deliver other functions like controlled discharge, storage, internal resistance measurement and so on.
Drone manufacturers usually deliver their charging solutions, sometimes very simplified ones, that do not provide, i.e. "storage" function, thus causes quick battery wearing out (i.e. Yuneec). Some other provide batteries with "intelligence" that discharges themselves automatically to the "storage" level, if not used for a long time (i.e. DJI).

Figure 139. LiPo universal battery charger

In UAVs, there is a variety of different power connectors. It is mostly related to different origins and a wide range of currents the plugs need to handle. Each connector has some maximum current rating, and their name usually explains it, i.e. XT60 is up to 60A. For this reason, universal chargers usually come with a bunch of cables and converters, virtually enabling you to charge any battery without the need for soldering (Figure 140). Of course, manufacturers deliver battery packs with their own, usually proprietary plugs but it is common to find third party adapters that will enable you to use universal and more advanced chargers instead of those provided by the manufacturer. Fortunately, for universal batteries, balancer connectors are standardised (so far there is one niche, different solution, used by Czech manufacturer Pelican) and it is JST standard plugs (Figure 141). Plug size is related to the number of "S" and the rule of thumb is a number of connectors is a number of "S" + 1.

Figure 140. Power cable adapters for variety of different, high current plugs

Figure 141. JST plugs for balancer

10.6. Communication, Remote Control and Autonomous Flights

A general idea of a UAV is to move in 3D airspace. It can be manually controlled via remote, usually a human operator, or an autonomous flight with various autonomy levels. According to the Drone Industry Insights (2019. https://dronelife.com/2019/03/11/droneii-tech-talk-unraveling-5-levels-of-drone-autonomy/) there are 6 levels of drone operations autonomy, as we presented in the introductory chapters on autonomous flying and ground vehicles. Regardless of the autonomy level, communication between UGV and UAV ecosystems are crucial for the reliability, durability and safety of the operations. For the performance, in case of the cutting edge cases like drone racing or collision avoidance. In the following chapters, we present various aspects and communication protocols used in drones.

10.6.1. UAV Communication

UAV ecosystem uses many levels of communication protocols. Starting from on-board communication between systems, through aerial-to-aerial and aerial-to-ground, finishing on satellite communication. Communication in UAV operations is essential to its safety, reliability and performance. Here we discuss the most popular communication protocols used in drones (Figure 142).

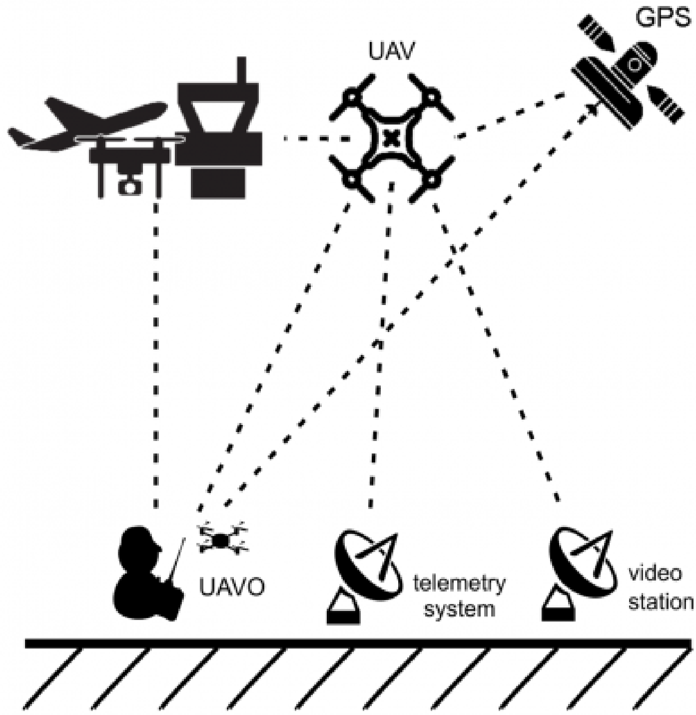


Figure 142. UAV communication general schematics

10.6.1.1. On-board protocols

On-board communication protocols are used to exchange communication between the drone components, usually flight controller (FC), sensors and actuators. Those protocols are commonly known and shared with UGVs and IoT world, so we just briefly present their list here without in-depth review.
Actuators are specific for drones; however, we discuss them in the following sub-chapter in-depth, along with remote control protocols (RC protocols).
The most common on-board, low-level communication interfaces and protocols are:

- I2C,
- SPI,
- Serial/UART (COM),
- CAN (not so common),
- One-wire (rare).

The exact protocol use is usually driven by the set of sensors and components present onboard the UAV. Flight controller sometimes exposes set of dedicated ports (connectors), sometimes they are universal plugs that can be used as configured in the FC configuration.
In many cases, an elementary set of sensors is integrated with the FC, Additionally, for GPS positioning, NMEA protocol is frequently used.

10.6.1.2. Remote Control and Actuators Communication Protocols

Remote Control is an essential part of drones. While there do are fully automatic systems that take-off, implement the mission and then land 100% automatically, in any case, there is a backup solution using manual operation such as RC control. Additionally, following mission progress and current system conditions is essential; thus, telemetry is a natural part for all flying objects, whether they perform autonomous or remote-controlled flight at the moment.

As from the beginning, RC was used to control actuators directly (usually control surfaces), so actuators communication protocols were and still are an essential part of the on-board communication. In Figure 143 we present a list of protocols and their assignment to the sections of the control sequence.

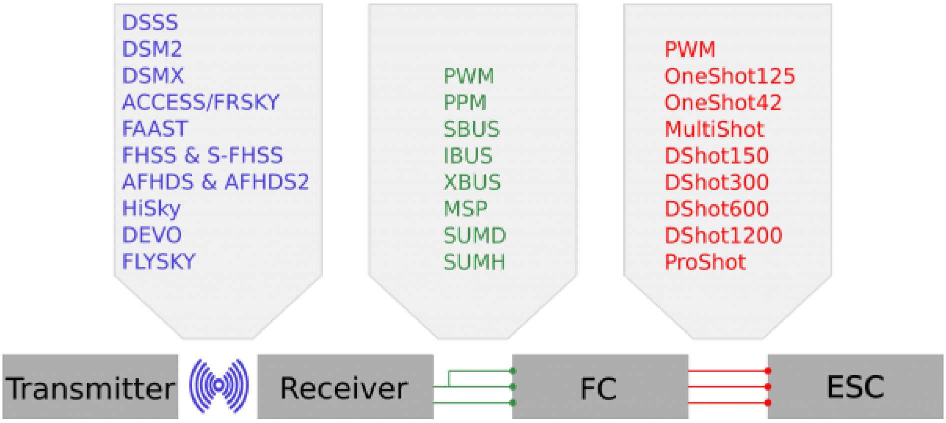


Figure 143. RC communication protocols

Regarding colours used in Figure 143, blue corresponds to the *RC Radio Protocols* section, green to the *RC Onboard Protocols* section, the *Telemetry* section applies to green and blue, while red corresponds to the *Actuators* section, as presented below.

10.6.1.2.1. RC Radio Protocols

Remote control units communicate over FM radio one or bidirectional way, from the Ground Station/Controller to the aerial unit, referred to as a Receiver, even if nowadays links are bi-directional and both parties play the role of transmitter and receiver.

On the physical level, we distinguish "analogue" RC that is (or rather "was", as it is rare to find users now) operating on 27MHz and 25MHz bandwidth. This kind of communication couldn't share radio bandwidth, so every pair (transmitter+receiver) sharing the same radio space needed to use a slightly different frequency, not to interfere. Transmitter and Receiver had both exchangeable oscillators, and it was pretty common; operators sharing common space had first to agree, who is using which frequency. That was rather uncomfortable in use. For those reasons, the analogue transmission is mostly abandoned now, even if its great advantage was a long communication range, virtually up to the horizon.

The Digital era brought the use of 2.4 and 5.8 GHz open frequencies. As transmitters and receivers became more complex, computerized and smart, many protocols introduced "channel" hopping, changing their frequency actively during operation once the interference has been detected.

Radio communication between Transmitter and Receiver is mostly manufacturer dependent, but the following ones are most common:

- DSM family by Spectrum. Spectrum is considered to be a highly reliable radio manufacturer:
  - DSMX - latest of "DSMs", also available as cheaper hardware from Orange manufacturer. DSMX is a new version of DSM2 and is backwards compatible: DSMX Transmitter can handle DSM2 Receiver. DSMX uses up to 60 channels.
  - DSM2 - also by Spectrum, uses two frequencies to transmit data.
  - DSSS - a single channel, rather old technology by Spectrum. Channel is selected and fixed during whole transmission, opposite to the FHSS model (see remark below).
- ACCESS / FRSKY by FrSky RC, bringing, i.e. automated re-binding and up to 24 channels.

- FAAST by Futaba - 18 / 14 / 12 channel ones (18 channel is 16 linear + 2 binary), 12 channel is fastest one with legendary reliability.
    - FHSS and S-FHSS - new frequency-hopping spread spectrum protocol by Futaba, replacing FAAST.
- A-FHSS by HiTEC - similar to other manufacturers, another spread spectrum frequency hopping technology.
- AFHDS and AFHDS2 by FlySky - another RC protocol, the second one offers telemetry (bi-directional). Pretty popular due to the cheap hardware.
- HiSky protocol - used in popular WL Toys.
- DEVO - used in Walkera products (former are WK2401/2601/2801 currently abandoned).

FHSS (Frequency-Hopping Spread Spectrum) - in short, it is a technology that pseudorandomly changes transmission radio frequency over the available spectrum (the sequence is known to both Transmitter and Receiver).

10.6.1.2.2. RC Onboard Protocols

Most popular RC protocols, once decoded by the RF, connecting Receiver and Flight Controller include:

- PWM (Pulse Width Modulation) historically that is the most popular protocol and still a kind of backwards compatible "backup" that most devices can still "understand" - the major disadvantage is, every channel requires separate wiring. Hence, it is not suitable for miniature drones.
- PPM (Pulse Position Modulation), also referred to as CPPM - similar to PWM, but it is not the duty cycle (as in PWM) but "distance" of the fixed pulse from the ticks defined by the clock signal; As classical PWM pulse takes between 1ms and 2ms max, and the 50Hz frame gives us 20ms, it is (theoretically) possible to send up to 10 channels, ordered. This is limited as the frame itself also requires some "space" between pulses. This way, PPM "queues" channels and send information about more than one in single wiring, one after another. Thanks to it, there is only one data wire necessary to connect the Receiver and FC. PPM has 250 distinguishable values resolution and about 4ms jitter.
- PCM (Pulse Code Modulation) - similar to PPM but fully digital transmission (binary), can detect errors.
- Serial protocols that include (among others):
    - SB US - in general, it is an inverted UART signal. Used mostly in Futaba and FrSky Receivers. Up to 18 channels. Some FCs struggle to invert UART (i.e. STM32F4 lacks inverters on GPIO inputs), so implementation requires external hardware to invert it back to standard UART signal.
    - IBUS - as SBUS, but plain, can be connected and decoded to any UART (used in FlySky Receivers). Two-way communication, one channel for actuators, the other for sensors (telemetry).
    - XBUS - serial implementation by JR, up to 14 channels.
    - MSP (Multiwii Serial Protocol) - a standard for communicating with FCs, allows you to "inject" RC commands from, i.e. ground station software. MPS is available as software libraries and present in many ground station implementations, both open source and commercial.
    - Crossfire - recent protocol by TBS, also similar to SBUS but includes telemetry.
    - SUMH and SUMD - serial, digital protocol by Graupner.
    - FPort - a collaborative work of FrSky and Betaflight (FC firmware) developers to bring one-wire, bidirectional communication between Receiver and FC.

10.6.1.2.3. Telemetry

Telemetry is all about informing the operator on the current UAV and mission status. For this reason, FC, and eventually Receiver, collects data from sensors and send it back via downlink to the Ground Station Controller/Transmitter.

As mentioned above, telemetry protocols on the local level correspond with Receiver-to-FC communication (if the protocol supports it). Still, if the specific protocol does not contain bi-directional communication nor telemetry, sensors are eventually connected to the separate port (usually another UART) in the Receiver. It is the Receiver's duty to collect it and send it to the Transmitter. Nowadays, most FCs can connect external sensors and Receiver-to-FC protocols used are those bi-directional ones.

Telemetry data can be sent directly via the bi-directional RC link on the radio communication level, so they mostly use 2.4GHz transmission. Eventually, it can be sent with a separate downlink, parallel to the RC link, using dedicated Transmitter-Receiver pair (note, here Transmitter is in the drone, Receiver in the ground station). In most cases, it is a UART over the radio, operating on publically available frequencies, mostly 433MHz and 868MHz/915MHz.

Note, those frequencies vary by geographical region: while 433MHz is a worldwide standard, 915MHz is used in part of Asia and the US/Canada, while forbidden in the EU. On the opposite, 868MHz is common in Europe but forbidden in the US. Be careful when ordering modules.

10.6.1.2.4. Actuator protocols

It is a set of protocols that drive servomotors and Electronic Speed Controllers (thus indirectly, motors). So far, in the case of the majority of servos, there is just one solution, old fashioned PWM signal. In the case of ESCs, it is not so straightforward as modern ESCs are programmable and deliver feedback on motor rotation; thus, most modern ones use bidirectional communication between ESC and FC. ESC protocols are sometimes referred to as “motor protocols”. The ESC protocol's main purpose is to “tell” the ESC how fast to spin the motor.

10.6.1.2.5. ESC Protocols

Those are protocols that indirectly drive motors. In the miniature brushed motors and early RC ESCs for brushless motors, FC was using PWM signal, as in servos. It is no longer a case, as ESCs are using microcontrollers and their features are programmable. Modern ESCs deliver backwards to the FC information about motor status, temperature, configuration settings and so on, so requires complex protocols, bi-directional. Here we present a list of the most popular ESC protocols:

- Analogue (pulse length based) protocols include:
  - PWM - as mentioned above, historical, still operating. Many ESCs can use it as a fallback if there is an advanced protocol's incompatibility between ESC and FC. It is worth mentioning that there are actually two PWM ESC protocols:
    - Analogue PWM, where 0% duty cycle is equivalent to motor stop, and 100% is equivalent to full throttle;
    - Standard PWM (as in servos), where 1ms duty cycle is motor stop and 2ms if full throttle. However, differently as in servos, the motor requires faster updates, so the PWM frequency is usually much higher than the servo's 50Hz standard. As 2ms it “full throttle”, the maximum possible PWM frequency is 500Hz.
  - OneShot family: OneShot125 and OneShot42 - for OneShot125, the pulse length is between 125 and 250 microseconds; thus, the maximum frequency is 4KHz; for OneShot42, the pulse is 42 microseconds, so it is 12KHz maximum frequency
  - MultiShot - it is 32kHz operating one, 10x faster than OneShot125. It is the fastest one in the family, but there are not so many ESC capable of handling it.
- Digital, binary protocols:
  - DShot family: DShot150/300/600/1200 - a family of digital protocols with 150Kbps (DShot150) to 1200Kbps (DShot1200) transmission speeds, respectively to the protocol variant. They use 4bit CRC to check communication for any errors that may appear, i.e. due to electromagnetic interference.
  - ProtoShot - an approach to integrate both digital (as, i.e. in DShot150) and analogue (OneShot) protocols, all in one.

Use of analogue protocols requires throttle calibration (setting motors not to spin at all and spin with their maximum RPM). Digital protocols do not require throttle calibration.

10.6.1.2.6. Servos

Servos are connected with 3 cables, power (+/-) and control. PWM frequency is constant, but it is the duty cycle that controls the servo rotation. Analogue (classical) servos use 50Hz PWM frequency. Modern, digital servos use 300Hz and up.
As digital servos are still not very popular, here we describe analogue servos' control principals. Analogue servo uses PWM standard frequency that is 50Hz, so the period is 20ms. A 0-degree rotation angle is equivalent to the 1ms high/19ms low digital control signal duty cycle, while 180 degrees is for a 2ms duty cycle. Naturally, this scale tends to be linear, so 90 degree is equivalent to 1.5ms: see figure 144 for graphical representation of the control signal.

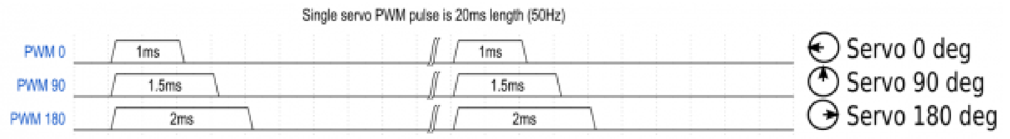


Figure 144. Standard servo duty cycle explained

As one can see from the above, the most common case is a servo operating on the 0..180 degrees range. Servos with other rotation range may use different duty cycles.

10.6.1.3. Video

Here we consider a video downlink. Regarding technology, we distinguish two types:

- analogue transmission,
- digital transmission.

Even if it seems to be obsolete, the analogue transmission has a great feature that is zero (or close to zero) latency. This is important in FPV racing and applications that require immediate response, close to realtime. This kind of video encoding is one of the old fashioned analogue TV, PAL and NTSC standards. Encoded video stream is sent via open radio frequencies, most commonly using 5.8 GHz. The standard resolution is 576 lines for PAL and 480 lines for NTSC, both interlaced.

The digital video transmission in amateur and semi-professional solutions include video encoded with one of the popular "computer" codecs, MPEG, H.264 and recently H.265. The majority of solutions transmit the digital video stream via WiFi connection, usually using UDP protocol. For this reason, the range is limited and strongly affected by nearby WiFi environment, i.e. access points. The transmission frequencies are 2.4GHz and 5.8GHz. Resolution is up to 720p, but recent encoding advances present the ability to deliver 1080p to the ground station. As in most cases, the device used to display the image is just a mobile phone; it is unnecessary to transmit a high-resolution stream, record it locally in the drone and then download it once the mission is finished.

There are multi-channel, professional downlink solutions available, like, i.e. DJI Lightbridge, obviously with a high price in case of the advanced semi-professional cinematography. Professional, high-grade solutions for live broadcasting from the sky use DCI transmitters to deliver stable 4k video directly from the sky. Still, those are available for extreme prices and limited in use for large drones only, as this kind of link consumes a huge amount of energy.

10.6.1.4. Other Communication Protocols

Many communication protocols are shared with IoT, computer networks, the automotive industry, UGV, airborne systems and even the space industry. Here we focus shortly on those used in drones or are on their way to be used in the nearest future.

10.6.1.5. Satellite communication protocols

Obviously, satellite communication protocols are frequently used in terms of drone (and operator) positioning. While it is possible to receive raw satellite signals over the radio and use it to decode the signal and obtain a lon/lat position using the triangulation method (see the chapter on navigation for more details), it is common to rather use ready GNSS (also referenced as GPS) receiver module, that communicates to the flight controller or other device, providing 2D/

3D position (3D includes altitude), positioning accuracy, number of satellites in view (it directly impacts positioning quality) and so on. Manual decoding requires a huge amount of resources, thus is implemented with integrated circuits. Here we focus on communication between an FC and GNSS receiver rather than between satellites and receiver.
GNSS modules use textual and binary communication, depending on the particular receiver chip and PCB board design. In particular, most GNSS receivers can deliver information using NMEA protocol that is a standard communication protocol at the moment, usually in a textual form over the serial connection (the most common is 9600 bps). At the moment, a binary communication protocol is being introduced as more efficient and simply delivering position data much faster, yet it is still a niche solution.
Sample NMEA data for Tallinn/Estonia Old City Central Market square is present below:

```
$GPGGA,095531.290,5926.238,N,02444.715,E,1,12,1.0,0.0,M,0.0,M,,*6A
$GPGSA,A,3,01,02,03,04,05,06,07,08,09,10,11,12,1.0,1.0,1.0*30
$GPRMC,095531.290,A,5926.238,N,02444.715,E,,,100920,000.0,W*74
```

Receivers are free to use (you do not need to purchase any licence/contract), and they're able to position using multiple satellite constellations.
Obviously, there are additional services(i.e. improved quality on positioning) that are charged for use, and it may be reasonable to use them in some scenarios.
Additionally to the satellite communication, there is also aerial and satellite communication that provides additional live data, i.e. related to the correction of the impact of the current state of the ionosphere, ephemeris, and other factors causing incorrect and inaccurate positioning. Those are handled by GNSS receivers and too complex to provide them here, but please note, they constitute an important factor in the quality of the drone positioning and is essential to the precise and secure operations and their performance in most scenarios.

10.6.1.6. ADS-B

ADS-B (Automatic dependent surveillance-broadcast) is an airborne protocol that drones barely use now, but that is changing over time. Each commercial aircraft broadcasts information about its current position, velocity, direction, and so on that can be received using special modules or even out of tuned DVB-T receiver (USB TV stick). ADS-B can be freely received and decoded, but it is forbidden to broadcast it without permission and licence. Communication uses a 1090 MHz band.

It is free to receive ADS-B, but it is forbidden to broadcast ADS-B. Broadcasting requires certified equipment and is done concerning the flight control and flight information services!
The simplicity of reception of the signal caused open-source implementations and the rise of flight information services like, i.e. very popular FlightRadar24 that directly benefit from ADS-B reception via distributed receiver network operated by amateurs.

Theoretically, ADS-B can be used to implement a collision-avoidance system once FC is aware of other aircraft in its nearby area.

10.7. Drone Simulators

Drone simulation software is recently more and more popular.
So far we distinguish two main purposes for drone simulation:

- Research and development;
- Operator's training.

Before moving to the details it is necessary to present some information in general: flight simulator is not only the software, running on the computer to visualise and entertain users: the common purpose is practice and development/experimentation to avoid risks related to the real world development where i.e. faulty firmware or software can break construction, hurt people and cause damage. This is important for both UAVOs and constructors/developers but their requirements are different. For this reason, we split drone simulators for two categories. Obviously, many of them can act as both.

Simulation for research and development usually requires the inclusion of the other components, more than just the simulator itself, but also other software and hardware i.e. ground control stations and RC controller. For this reason, this class of simulators include the ability to simulate autonomous flight and involves popular hardware to be used as in case of a real drone.

In details, this includes the use of the FC (most common is PX4 along with MAVLink protocol but other FC stacks are also supported, i.e. Ardupilot) as a part of the simulation, in opposition to the simulators for UAVO training only, where hardware use is limited with connecting an RC controller to the PC simulator at most, simply replacing the joystick to make the simulation as much realistic for the UAVO as possible.

There are two types of inclusion of the FCs into the simulation process for research and development simulation class: HIL / HITL (Hardware-In-The-Loop) and SIL/SITL (Software-In-The-Loop).

10.7.0.1. HITL

In the case of the Hardware-In-The-Loop, a physical FC device is connected to the simulator. Obviously, it uses only some features of the FC, i.e. use of IMU or connected GPS is impossible as hardware physically is stable and located in one place. It is common that FC interfaces with at least RC receiver and RC transmitter, to let the user/operator perform operations. As FC interfaces PC simulator, the common communication port is then excluded so it may not be possible to integrate easily with ground control station solution but that varies (Figure 145).

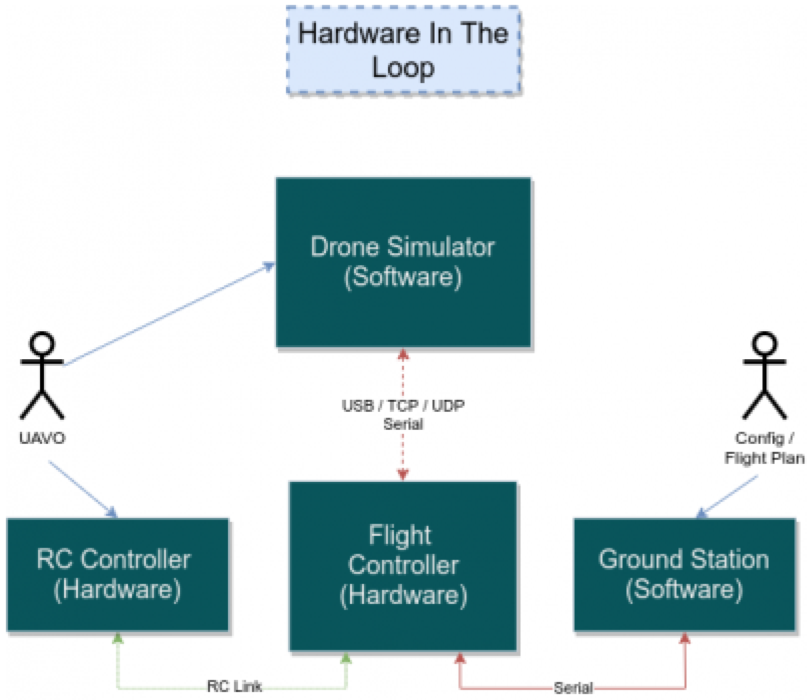


Figure 145. Hardware in the Loop

10.7.0.2. SITL

In the case of the Software-In-The-Loop, FC hardware is replaced with a software module, usually running as a separate virtual machine (or Docker container). For PX4 SITL it is always Linux solution, even in case of the simulator running under Windows. Figure 146 presents schematics.

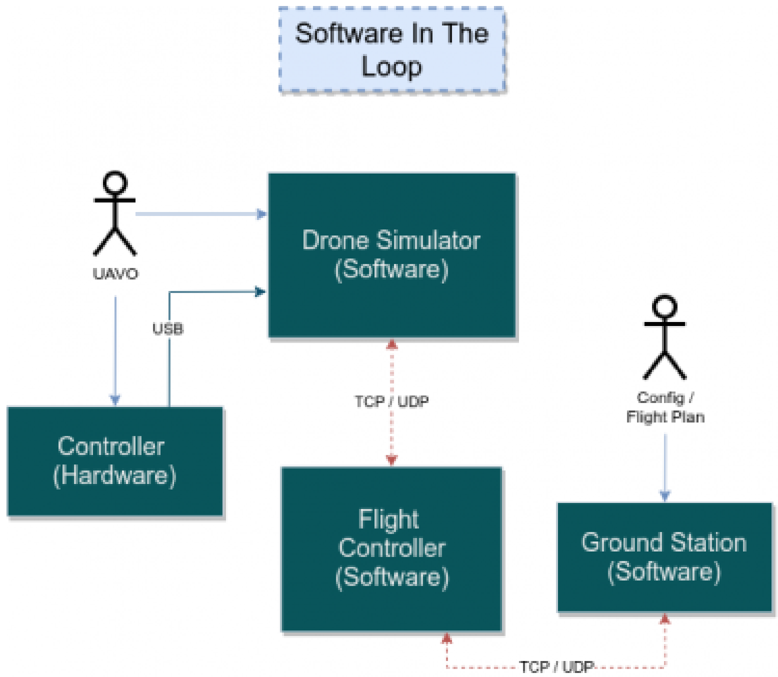


Figure 146. Software in the Loop

10.7.1. Simulators for research and development

At the moment, there are multiple solutions, but the following simulators are freely available thus they are popular among a variety of users:

- AirSim by Microsoft (still Open-Source): https://github.com/microsoft/AirSim; This simulator is also suitable for UGV, not only for UAV, and its purpose is mostly to implement and test high level, AI-related solutions for autonomous vehicles. AirSim can integrate with ROS-based hardware (Robot Operating System) solutions. As it is implemented using popular gaming Unreal Engine (Unity based version is on its way to the users), the graphics is astounding yet it requires a powerful GPU to run. The simulator provides rich user experience with a natural-looking environment like interiors, cities, streets, parks and so on (Figure 147). AirSim integrates seamlessly with PX4 hardware (HITL - Hardware In The Loop, a limited number of controllers) and PX4 software stack (SITL - Software In The Loop).
  - Supported frames (models): Multirotor, vehicle, Quad-X for PX4.
- GAZEB O was developed as pure Open-Source simulator for a variety of physical devices, also for UAVs and UGVs, but not limited to: http://gazebosim.org/; Its origin is to simulate robots. It provides simple graphics (Figure 148), but the benefit is it can run on constrained hardware. The GAZEBO seamlessly integrates with the ROS environment. The simulator also provides ORCE rendering engine for a realistic environment rendering, but the real power is simulator's flexibility on configuration and simulation running, starting from constrained Linux-based machines, finishing on Amazon AWS, cluster and cloud-based simulations. GAZEBO provides a variety of physics engines to choose between.
  - Supported frames (models): Quad, Hex (Typhoon H480), Generic quad delta VTOL, Tailsitter, Plane, Rover, Submarine.
- FlightGear: https://www.flightgear.org/ an open-source, multiplatform and far beyond drones flight simulator with decent physics. Supports integration (via external tools) with Software-In-The-Loop (SITL) implementation of PX4 thus is suitable for mission planning as AirSim. FlightGear supports multi-vehicle simulation.
  - Supported frames (models): Planes, Autogyro, Rover.

- JSB Sim: http://jsbsim.sourceforge.net/index.html is and FDM implementation (Flight Dynamics Model) without visualisation frontside. Yet it can be integrated with i.e. FlightGear. JSBSim is in fact a mathematical and numerical model of the aircraft and its physic. Model simulation is highly advanced and based on the numerical data obtained from the number of experiments performed within the wind tunnel, so highly realistic.
  - Supported frames (models): Plane, Quad, Hex.
- jMAVSim is a simple simulator for multi and quadrotors only, with a simple environment. It can include in the simulation PX4 FC, in both HITL and SITL scenarios and supports multi-vehicle simulations.
  - supported frames (models): Quad.

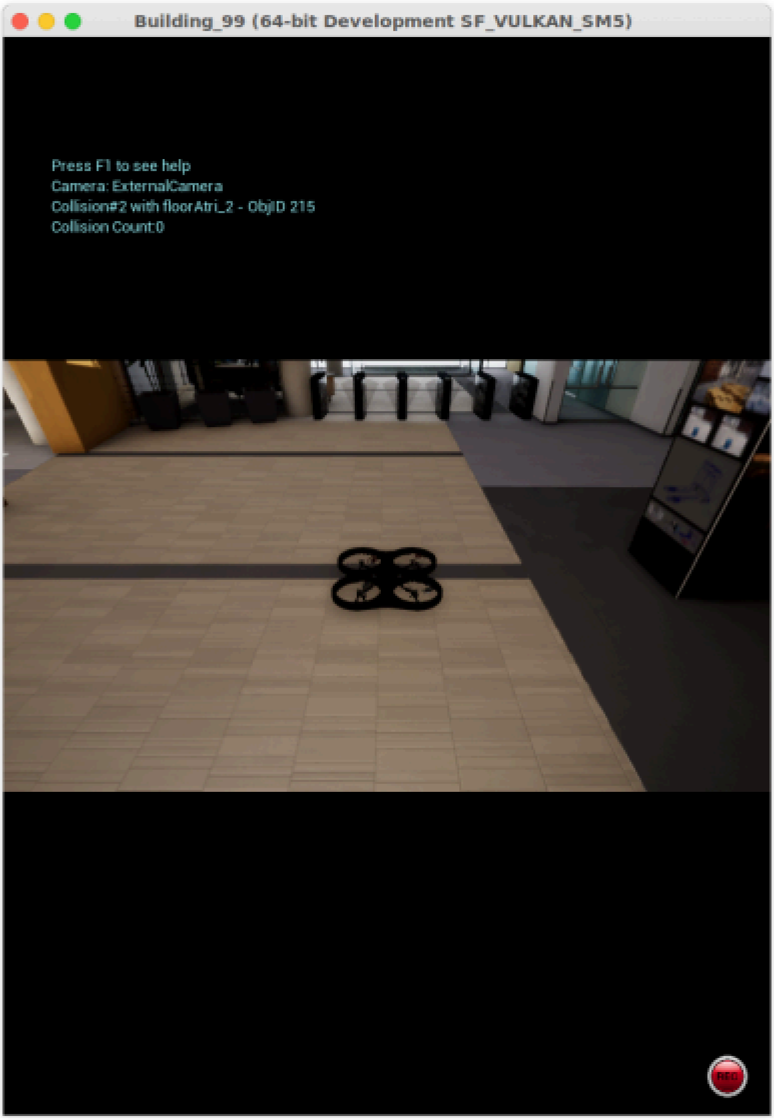


Figure 147. Microsoft's AirSim simulator

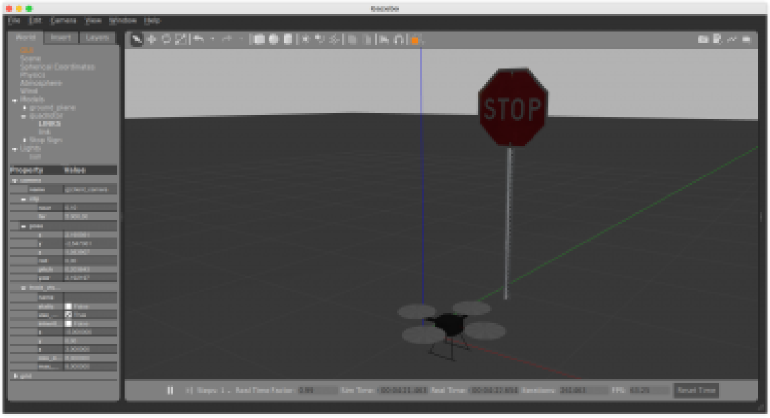


Figure 148. GAZEBO simulator

10.7.2. Simulators for training of the operators

Many inexperienced operators found it useful to practice first, using virtual equipment, where any crash is virtually costless in opposite to the real devices.
For this purpose, many drone vendors provide simulators for training, i.e. DJI and Yuneec.
Most of the drone simulators of the operator's training class use a simplified physics model and graphics, that results in not so realistic UI in terms of simulation and graphics quality, yet good enough to practice operator's reflexes.
Use of this kind of simulators is obligatory in many countries when practising and preparing for professional UAVO certification, as the first step towards practical, outdoor part of the training.
Some simulators are composed just like a playground area for model flights while advanced present scenarios the virtual operator is supposed to implement, also verified in time and space, including time-limited and quality evaluated virtual exams. Simulators of this kind used to provide various airframes to choose between, different camera positions, i.e. one can observe the drone from the ground, or use the onboard camera, simulating FPV flight, and so on.
It is a common approach, that simulators are somehow open to connect any controller, as they used to be able to use regular Joystick/Game controller that is visible in the operating system. There used to be a hardware, mostly USB-based receiver that is capable to act like FC, where you can connect various Receivers thus use your own Controller. This approach introduces the natural latency of the RC link and use of your familiar controller but that also requires some configuration of binding RC channels with appropriate software functions. A non-exhaustive list of training drone simulator is juxtaposed below:

- DJI drone simulator: with great graphics, but limited to some of the selected DJI models.
- Zephyr: commercial and expensive, compatible with FAA regulations, FPV and VLOS. Supports game controllers and professional RC controllers. Used in the US for training.
- droneSimPro: commercial, inexpensive but limited to XBOX and PS game controllers.
- Phoenix R/C Pro: commercial, expensive, supports over 200 different airframes including multirotors, helicopters, soarers and planes.
- RealFlight: commercial, pretty expensive yet delivers a variety of scenarios and missions to do. Great and "lifelike" physics simulator (perhaps best on the market) including day/night, wind and gusts, and so on.
- Quadcopter FX: cheapest, not very versatile but good enough for beginners to practice elementary operations.
- Drone Racing League SIM: designated for FPV only.
- Hotprops FPV: not so advanced as aforementioned Drone Racing League, still for FPV beginners it is a good choice. And it is free, for Android.
- AeroSIM RC: versatile simulator with many versions including examination centre for EU UAVO training centres (Figure 149).

Figure 149. Aerosim RC drone simulator

Most of those simulators use HITL model only and hardware supported is usually limited to the proprietary.

10.8. Drone market statistics, analysis and forecast

Most countries consider the UAV market and related development and sales as one of the key components of GDP growth. The drone market value is estimated at 22 billion USD in 2020 and is expected to grow almost twice by 2025 [60]. This is mostly related to the recent R&D and technology progress, once the implementation of the tasks requiring a high level of autonomy became possible and affordable.

At the moment, we somehow observe in many developed countries saturation of the drone operators for popular tasks like video filming, movies, in general, those requiring RC. Yet the market opens for fully autonomous systems, and it is also possible, because of the ongoing regulations and standardisation on the use of the air space by autonomous UAVs, including Europe-wide standardisation (see the chapter on regulations).

Interestingly, the Fortune Business Insights reports on drone software market size to be around 6bln USD by 2027 (1.2bln USD in 2019). As the driving factor, the report mentions increased adoption of the AI (Artificial Intelligence) in both drone operations and data processing, grabbed by UAVs [61].

This optimistic growth is affected by the following factors:

- Lack of worldwide (as in case of passenger planes) regulations on the airspace use, communication equipment and utilities for autonomous flights: many individuals and companies defer the decision to buy UAV hardware, considering future incompatibility of their purchase with coming regulations, unknown at the moment.
- Large market fragmentation: with some leaders (i.e. DJI for commercial and recreational devices) and other competing companies, trying to find a niche.
- COVID outbreak, that affects delivery chain thus hardware availability (on the other hand, COVID outbreak caused demand on contactless delivery, where drones fit perfectly).

In general, it seems that in most countries, the market for skilled UAVOs, using RC only flying modes is rather saturated. However, we predict the demand for new positions with a requirement to handle drone operations with a high level of autonomy. Those positions will naturally expand from the manual (RC) only UAVOs, along with the growing complexity of the operations.

This applies straightforwardly to the drone utilities and services sector, including specialised drone constructions and growth of universal platforms that can be converted virtually to any requirement, not only, i.e. different types of cameras but also several sensors and actuators.

We also predict that growth will happen if software houses, delivering navigation solutions for autonomous flights, integrating drones with U-Space (universal airspace where all flying objects can avoid collisions, the best, automatically), enabling precision manoeuvring that is computer vision-based.

At the moment, the hardware commercial drone market seems to be dominated by Chinese manufacturers, in particular by DJI (about 70% of the commercial market, as for October 2020). Other manufacturers focus on the niche solutions, eventually are trying to compete in the limited range, like, i.e. solutions for professionals and the semi-professionals, as in case of Yuneec. For this reason, commercial drone hardware manufacturing is hard-to-compete, so it is possible to launch a new business for a niche, industrial solutions.

10.9. UAV operations characteristics

Regarding the range of the operations and requirements for the hardware and software, there are 3 major classes of the UAV operations:

- VLOS - operations within Visual Line Of Sight;
- BVLOS - operations Beyond Visual Line Of Sight;
- FPV - First Person View.

We provide summary and characteristics in the following sections.

10.9.1. Flying VLOS

The VLOS flying is the first drone operators use. And the most common one, requiring the lowest level of certification or no certification at all (depends on the scenario, UAV weight, flight region). The most common question is “How far can I go?”. It depends on the regulations, drone size, weather conditions and many others, but in any case, the best approach within the formal limits is given by the following rule: VLOS flying requires UAVO to be able to see and orient the platform using the naked eye [62].

When flying VLOS you not only need to see, where the drone is now, but also need to know it's orientation.
VLOS flying does not necessarily mean you need to control the drone in RC: you can use even high level of autonomy modes, but you need to see the drone and be ready to “jump into the action” when needed, i.e. to avoid the collision with another object or modify trajectory. For this reason, VLOS operations require constant observation. In many countries, regulations allow using additional human observers, supporting UAVO during operations. Note, in any case, it is UAVO's responsibility for incident or accident.

As mentioned before, flying VLOS may use virtually any mode from fully manual to fully autonomous. For this reason, a variety of drones fits this category. Depending on the flight mode, there are different requirements for the UAV aerial section and ground section hardware and software, as discussed in the hardware section.

It is also natural and allowed by regulations, that UAVO can stop observing the platform for a moment, to check telemetry and ground control systems. Still, in any case, he/she must recover sight contact with the drone quickly, which may be pretty difficult if the platform is far away.

10.9.2. Flying BVLOS

Flying BVLOS requires more advanced certification than VLOS. It also requires a higher level of communication capabilities between the aerial section (UAV) and ground section (UAVO). The operator needs to be able to control, trace the current location of the drone, and introduce necessary actions remotely. For this reason, the majority of the solutions require good video link (sometimes with multiple cameras/streams). This type of operations has a strong demand on the system reliability, so drones used in BVLOS usually have at least duplicated or even tripled navigation and IMU systems and reliable communication solution. Note, flying BVLOS is flying beyond the horizon of sight, within the line of sight but out of sight range, but also, i.e. beyond the construction (like, i.e. a building). All of those situations require more advanced communication systems than in the case of VLOS drones.

Majority of modern VLOS commercial constructions are ready for BVLOS or at least can be easily adapted. Note, forthcoming regulations will require drone identification using certified devices to let them broadcast ADS-B communicates (as in the passenger planes). More on ADS-B, one can find in Wikipedia [63] and FAA websites [64]. Please note, using ADS-B transmitter requires certification and drone registration while receiving ADS-B from others is considered to be free. And latest FCs contain integrated receivers like i.e. Pixhawk Orange Cube.

In the BVLOS operation, UAVO uses ground station solely and does not observe the drone. Hence, it requires to provide all necessary information to the operator and also to be able to deliver commands to the UAV reliably.

10.9.3. Flying FPV

Flying FPV origins from the racing, where the operator is “virtually” sitting as a driver or rather a pilot, within a drone's cockpit. Indeed the operator uses a distance video link to see the footage from the front-mounted camera. FPV drones usually do not provide advanced obstacle detection and critical situation handling capabilities, so flight range is limited by law.

It is worth mentioning that most FPV flights are performed as fully manual controlled ones, even without self-levelling and altitude hold. For this reason, FPV pilots require great skills on space 3D imagination, deep understanding of the flight physics and most of all, huge experience. FPV racing is also considered the class of flights where collisions frequently occur, even leading to the total drone damage. For this reason, FPV racing is performed on the dedicated tracks, and pilots are practising away from humans and properties to limit eventual damage cost.

Obviously, FPV can be used as a part of the regular, commercial drone operations, i.e., inspecting a power line.

FPV flying requires low latency video transmission link (usually analogue) for racing, but digital links are acceptable for non-racing operations, where low video transmission latency is not critical. Indeed, many manufacturers (i.e. DJI, Yuneec) offer FPV sets for regular drones, enabling users to switch from observing a video transmission on their controller/phone to the FPV glasses. While in the case of racing, FPV glasses/headset is a must.

When using FPV glasses/headset, the operator cannot see anything else, but the displays, so FC, related hardware or eventually ground station video processing unit must deliver all necessary information on the screen. That impacts the hardware requirements (usually FC) to let it be able to perform an OSD (on-screen display). Modern FCs that use ARM cortex core (i.e. STM32 F7 series) can deliver this feature out of the box, while there is usually an external, analogue video processing module that supports the FC in this task.

10.10. Drone-related job characteristics and applications

10.10.1. Job characteristics

In the following guide, we present job characteristics, directly or indirectly related to the drone market. It is important to remember, however, that this guide is non-exhaustive and somehow subjective, as drone market changes rapidly and also differs between countries. Details are present in the table 5.

Table 5. Job characteristics of drone-related positions

Job name	Short characteristics
UAVO - drone operator	Required manual skills to be able to control UAVOs, good sight and practice. Manual control of the drone is demanding, requires the ability to focus for a long time be precise and farsighted. A good three-dimensional orientation is a must, as well as understanding of the general flight physics. For the flight with a high level of autonomy, 3D imagination is required as well as a general

Job name	Short characteristics
	understanding of maps and planning software. At least elementary understanding of the weather processes is essential.
UAV designer/ implementor	As drone design is interdisciplinary, a person that targets this position is expected to have skills from various areas including physics, electronics, mechanization, mechatronics, software development and communication (in particular wireless one). Also, good mathematics basics are essential, and knowledge of the calculation and simulation software is an added value, i.e. to design, calculate and simulate wing cross-section.
UAV cameraman	In the professional cinematography it is common that UAVO and cameraman are two persons. In this case, UAVO is relieved from movie recording and photo-taking, but the cameraman is limited with drone physics and obviously, also uses the remote, distant camera. For those reasons, the cameraman should be in close contact with UAVO and requires extra skills including specific drone limitations like limited flight time, the limited payload for a camera, delays in controlling the camera because of using an aerial connection to it, limited range of the transmission and so on.
Video postprocessing specialist	A person that processes aerial photography and video materials. Nowadays, drone cameras offer decent stabilisation, but aerial photography and video filming is slightly different than regular movie recording, mostly because of potential instability (shaking), higher video compression, wider scene dynamics.
Volume object 3D scanner and processor	Drones are used to grab photos to obtain later a large scale 3D models (i.e. old buildings). A set of photographer skills are essential, good scene planning and precision flight planning and controlling skills are a must as it is common that drone must be able to reach to all details and photograph them from various angles. In this job, UAVO is usually the same person that operates a drone camera.
Infrastructure inspector (power lines, pipes, etc.)	Power line inspections usually require BVLOS skills and certification. Draft inspection can be done with a high level of autonomy, so ability to use flight planners and understanding of the environmental condition, reading maps and plans is essential. Precise monitoring (i.e. close inspection of the power cable bindings) is done with manually controlled flight to make a close approach, so ability to make precision manoeuvres and 3D orientation is important. At least elementary understanding of the weather processes is essential.
Drone educator	Drone education is very comprehensive and interdisciplinary: on the one hand, it requires at least elementary UAVO skills and knowledge on drone ecosystem components, on the other, good tutoring skills to create valuable and intriguing courses. As UAV education is very practical, teachers should hold practice in UAV operation, UAV construction, not just theoretical background. It also requires a good understanding of physics and weather environment. Obviously, that may be limited in case course covers only specific scope.
Drone serviceman	Working in drone service requires a set of manual skills on both mechanics, mechatronics, electronics and IT. There are two types of positions: those related to the specific manufacturer and those universal, based on open components. The other is rather a niche as many people building drones themselves are also willing and able to service them. Still, manufacturer services are rather popular among amateur users, buying RTF (Ready To Flight) products. Manufacturer-specific services and jobs are somehow easier as components are delivered by the corporation while working in an open, cross-platform drone service requires flexibility on replacing and substituting components and also following of the latest trends in the market as well as knowing and following current delivery chains for components.

10.10.2. UAV Applications

UAV applications increase over time, and so far, we find new application areas instantly. They appear along with enhancements in flight control logic and autonomy level rising, thanks to the technology development. Yet, there is several already well-known UAV applications that we describe below.

UAV applications in general share into the military and civil. We do not consider military-specific applications in this document. Many of them are common, however, and the line between military and civil application blends.

In general, a variety of UAV solutions suit many categories, but each category presents specific requirements regarding airframe type, flight duration, equipment, methods of control and flight mode. It is also notifiable, that applications differ by flight modes, in particular: autonomy level, operators' qualification understood as VLOS/BVLOS/FPV certification and most of all: operator skills.

In the following guide, we represent the UAV system characteristics, required for different applications. Details are present in the table 6.

Table 6. Drone applications characteristics and requirements

Application name	Short characteristics	Drone ecosystem hints on hardware
Drones in Education	Drones for education cover various levels, from elementary where young pupils learn on how to control UAV till higher education where students and researchers use drones for experimentation and development. For this reason, depending on the level of education, drones with API may be required. For the basic level, indoor, safe to fly drones are the best option while for little more advanced students, drones that can be controlled in the team mode (instructor can take over) is a good option.	Depending on the course level and purpose, education may require indoor and outdoor drones. For safety reason, rather slow and not so powerful ones are suggested. Indoor flying can start with cheap brushed-motor equipped drones, i.e. DJI Tello. For more advanced flying, DJI Mavic and Phantom are good options. Higher education usually involves custom constructions based on Pixhawk/Ardupilot capable FCs to fully enable the power of autonomous flight, programming and integrating various components.
Drones in Film-making	This class of applications cover both occasionally film making, i.e. during wedding and events as well as professional cinematography. Different skills are required, but in any case, reliable drone and rather some >250 g (usually much more) are needed to present stable flight. Drones with shared functionalities among two team members are required for professional cinematography, particularly during the recording of the dynamic scenes, where UAVO function is separated from the cameraman, so it requires systems able to bind two controllers. Because of the drone weight and recording places, it is necessary to present certification and flight skills. Filmmaking requires good operator skills, 3D imagination, some art-soul and a set of spare batteries to replace, as recording may need re-taking of the scene and there is usually many unforeseen obstacles that extend required operation time.	For occasional recording, any drone with at least full HD camera (usually at least 2.5k), i.e. DJI Mavic is enough. Note, many of those entry-level drones, even if providing great filming capabilities are limited with stabilisation and recording direction, as cameras are front-mounted, thus to make a pan filming, you need to rotate drone (yaw) that usually causes shaking and unstable recording due to the changing wind direction. For the professional operations, heavy drones (usually far over 5 kg MTOM) are common, and drones with good positioning capabilities (GNSS is usually enough, no RTK needed), decent gimbals and set of extra devices, i.e. servos and

Application name	Short characteristics	Drone ecosystem hints on hardware
		motors to control professional camera optics are required. An important feature is the ability to wrap/hide/fold drone's landing gear, to let the camera freely rotate under the drone (opposite, i.e. to the popular DJI Phantom, where landing gear is in FOV of the camera. Professional cinematography drones may cost a fortune. Entry-level drones start from DJI Inspire (some 6k EUR), DJI Matrice series 7-8k EUR) up to Freefly and xFold solutions, hitting with ease over 40k EUR for a platform.
Drones in Real Estate	Thanks to the drones, real estate benefits from easy aerial photo-taking, inventory and even 3D model making. Drones brought a new perspective that was never possible before. Recently, small drones are used to record in-door videos as from the perspective of the visitor, to present videos to the buyer. Real estate market often uses UAVO freelancers for it. This application has demand on good and high-resolution photos, and usually, max altitude is limited, so drones with wide lens cameras are needed. Also, post-processing (commercial, open-source) software and PC hardware to handle it is needed, i.e. video processing software like Final Cut, Davinci Resolve, Adobe Premiere and photo editing software like Photoshop, Corel, Gimp, Darktable is needed. Drones able to shot and save raw photos are advance here, as photo and video quality are essential. Operations are usually manual (with a low level of autonomy), so there is no demand for advanced ground stations. Long flight times are not necessary, and it is usually the ability to plan flight operation. A niche requiring autonomous and ling time flights is, i.e. dude ranches inventory where areas can cover up to dozen of a hectare. In such a case, there is a demand for autonomous flight capabilities and also long flight time, so it is considered to use fixed-wing FPV drones here.	Any entry-level drones of semi-professional class fits here and operations are mostly manual, so there is usually no need on additional components, i.e. ground stations other than RC suitable for operations. Sample drones that fit here are Yuneec Typhoon, DJI Mavic, DJI Phantom, Autel EVO. For the in-door flight, a drone with optical position stabilisation is needed, but compact in size. A good choice here is the DJI Mavic Mini. In the case of aforementioned niche solutions, fixed-wing drones are a good solution, i.e. Yuneec Firebird, Parrot Disco and so on.
Drones in Construction and Industry	Applications vary from the industry characteristics, but the most common is to use drones for surveying. Majority of operations require precision positioning; thus, RTK (Real-Time-Kinematics) enabled drones are essential. Also, infrared cameras are frequently required, but high-quality photos and videos are usually not necessary. Monitoring of the highway construction	Variety of drones fits this application, but it is common to see Yuneec H520 and DJI Matrice drones, as they are RTK enabled. The price for those drones usually is around 5k EUR or more, and IR cameras even pump up the price. For the highway inspection, it is

Application name	Short characteristics	Drone ecosystem hints on hardware
	requires flight on a long-distance and drones able to operate autonomously and those with long flight times are preferred. Often an orthomosaic and 3D mapping software is necessary for data post-processing. Some industry applications include special sensors to be mounted on the drone to check, i.e. air quality, gases and so on, or to send drones to the areas that are dangerous to the human, i.e. Fukushima / Chernobyl nuclear power plants.	considered to use fixed-wing ones, i.e. senseFly eBee, because of the extended flight time, easily getting up to 50min.
Drones in Public Safety and Monitoring	This class of application covers a variety of activities, starting from law enforcement, through critical situation management, disasters handling and fire fighting. Because of it, a variety of devices is needed with a vast number of functions. Commercial devices available out of the shelf are suitable for the majority of the applications, but some require specialised equipment, i.e. seeking for people trapped in the house under fire requires specialised IR/thermal cameras. Sample firefighter team may benefit from an aerial view to evaluate the on-site situation and make ad-hoc decisions on evacuation using commercial drones, while in case of the forest fires, covering large areas, a drone able to fly for a long time and distance is needed, probably a fixed-wing one would be a good choice. Police may use a drone to monitor the crowd and eventually, to check for possible evacuation and safe places, in a case of i.e. active shooting. A drone with good optics and high resolution as well as able to deliver quality photos and video in low light is needed. Many latest commercial drone constructions fulfil those requirements.	Many fire departments and fire law enforcement teams use regular, commercially available constructions, i.e. DJI Mavic and Phantom (the former one is perhaps most popular drone for firefighters used for an aerial overview). For large areas aerial inspection, requiring long flight times and distances covered, a good option is a fixed-wing drone, i.e. Autel DragonFish or Kestrel. Entry-level professional drone with the thermal camera is i.e. Yuneec H520 and even Mavic 2 Enterprise with a thermal camera and an extra spotlight.
Drones in Journalism	Drones in journalism bring the new layer of information and drama, thanks to the ability to present information in a wider scene, using aerial views. Whether it is still photography or video footage, using a drone is much cheaper than a helicopter and even enables aerial shots when it was previously impossible to get them whether to the high cost or other obstacles. As journalism present a wide number of needs, there is both demands on high-quality photo and videos while in case of the dynamic scene for TV news, drone performance and ability to transmit live video signal for a long distance is more important than image quality. In any case, vast of situations and working under pressure means a UAVO needs to possess top-notch flying skills. Most of the operations is done manually but indeed some artistic landscape shots use autonomy. An appearance of the mass scale social media	For journalism, a wide range of drones may be used. Amateur journalism for Internet benefits from small drones i.e. DJI Mavic Mini, as weighing less than 250g enables them to be in any backpack. For professional news, even top-shelf still amateur class devices are suitable i.e. Mavic Pro, Inspire series and for professional footage, FreeFly and DJI Matrice are suitable. In general, professional journalism shares common requirements with professional cinematography. Niche requirements include ultralight and silent drones that are able to fly imperceptibly to the animals, even butterflies, usually mimicking an animal - such

Application name	Short characteristics	Drone ecosystem hints on hardware
	journalism (Facebook, Instagram and others) forced commercial UAV manufacturers to include even simplest automation for the cheapest and smallest drones, i.e. a "selfie" function, where drone starts automatically, flies away, takes a photo of you and returns back. Larger ones benefit from other "programs" like i.e. "follow me", "orbit". This sort of features brought a new class of sports footage, where a single person can be a sportsman and a drone operator, simultaneously. A non-exhaustive list of common journalism drone missions includes breaking news, traffic reporting, documentary, photojournalism (including travel), sports, disaster reporting, investigative work.	constructions are individually designed and delivered.
Drones in Agriculture	Applications vary, from precise farming, through crop surveying till fertilization and spraying of the large areas. In any case, a majority of applications requires the use of industrial, heavy drones, usually because of a payload needed and distances travelled. Because of the nature of farming, most operations are performed with a high level of autonomy, usually BVLOS. Crop monitoring usually requires multispectral cameras, so commercially available drones are not suitable for this task, anyway, recently advanced image and video processing limits demand on specialised video cameras towards regular, and much cheaper solutions.	Variety of professional drone manufacturers tries to find their position in agriculture niche. I.e. Parrot manufactures a Parrot Bluegrass drone, equipped with Parrot Sequoia sensor (multispectral camera with 4 distinct spectral bands), dedicate to detect problems with a variety of kinds of crops. Also DJI offers their Agras and MG series as dedicated to the agriculture, i.e. Agras T16 (with 16l tank for liquid payload).
Drones in Transportation and Delivery	At the moment, drones are used in a delivery dual way: niche solutions i.e. to deliver medical tests from one place to another and in mass scale for the so-called last-mile-delivery of the goods. In any case, it requires a high level of autonomy (actually fully autonomous flights) and because of it, many countries delay the introduction of those solutions. Perhaps one of the first and key players in this field is Amazon, trying to lower costs, replacing human-based delivery with drones. Still, there are mostly no regulations enabling mass scale usage of aerial-based delivery and obviously, distance is quite limited here. In transportation, drones are used mostly for inspection and analysis, to get a bigger view of the problem (i.e. traffic optimisation, road planning). Drones also help here to inspect infrastructure i.e. railroads. This speeds up the process and lowers costs.	As applications vary, also equipment needs are vast. For transportation, i.e. railroad inspection, traffic monitoring, a commercial drone (i.e. DJI Mavic, Yuneec H520 and virtually any drone in a weight class of 2-5kg is suitable. Obviously, those models able to accept and perform autonomous flight plan are preferred, and a good visual imaging channel (camera) is a must. On the other hand, for the delivery, specialised, heavy lifters and energy-efficient drones with the ability to fly autonomously, detect obstacles and perform long flights are rather dedicated solutions like i.e. drones for the Amazon Prime Air delivery. As multirotors are not so energy efficient on long-distance deliveries, VTOL planes are considered to be a possible future solution.

Application name	Short characteristics	Drone ecosystem hints on hardware
Drones in Search and Rescue	Drones in SAR applications are nowadays a part of the game that cannot be usually excluded. Whether it is a search for a missing person in the forest, a lost climber in the rocks or a castaway on the sea, the drone can help to find a person and help to evaluate the situation and get to the person quicker. Also, in some cases, the drone can deliver i.e. medicament, medical equipment like AED (defibrillator) or even just water or food to temporary support the person in need. Variety of application has an impact on the drones used. In most cases, an infrared camera, a good video down-link presenting live high-quality video stream is needed, while this class of applications has early adoption of the AI-based tools i.e. to help to identify a person in need autonomously.	Some industrial-standard semi-professional drones are suitable but usually equipped with decent video cameras including thermal ones. There is a variety of drones fitting here, starting from DJI Mavic through Yuneec H520, towards heavier and more durable constructions, i.e. DJI Matrice series. SAR operation at the sea is usually performed during heavy weather conditions, during strong storms, so heavy drones and water-resistant solutions are needed here.
Drones in Entertainment	Drones used to entertain people for a couple of years but we do not consider here amateur operations (i.e. flying for fun) using commercial constructions. Two mass-scale applications in this class are drone light shows, as presented i.e. during the Olympic Games opening ceremony in China, and FPV racing leagues. Both focus rather on smaller drones, and while FPV racing uses gully manual flights, drone light shows use complex hardware-software solutions and hundreds or even thousands of same devices, flying in the formation - here, one of the first to be on the market was Intel, providing their solution as a service on demand. Nowadays, there are followers, and in many cases, solutions are based on the ROS (Robot Operating System).	FPV and formation flying focus on rather lightweight drones. Most of the FPV leagues use some 125mm-250mm frames, while formation flying drones are usually custom solutions, oriented towards lightweight constructions, able to fly autonomously and also being secure and safe - many of them introduce a cage that drones can physically hit one another with virtually no damage to it.
Other applications	There is practically an unlimited number of possible applications, i.e. in medical services and in the mid-future, passenger flights i.e. drone-taxis. Some early experiments are done with emergency services, i.e. drones able to deliver medicament to the person stuck in the high mountains, where there is no other help possible or it is delayed. Some early experiments with drones delivering AED (defibrillator) in Dubai city were tested, as drones are not stuck in a traffic jam, so they can reach accident place quicker than any human rescue team. There is also at least a single report that drone (here regular Mavic with modified propellers) was used in Himalaya mountains for delivering information and monitoring i.e. to observe summit climbers. Recently, some cities introduced agriculture-class drones to spray anti-viral liquids, to disinfect streets, bus stops and so on, because of the SARS-COV-2 virus outbreak.	Those constructions are usually unique, closely tailored into the niche problem they solve, and there is no specific guide here other than such drones usually carry a heavy payload, so some of the larger frames (i.e. Tarot X8, DJI Matrice S1000 and S600 may be used as a starting point for development.

10.11. A human operator (remote control and mission planning)

Even the best hardware and software may fail. So far, considering missions with even highest level of autonomy, there is always a human operator whether controlling a UAV directly or monitoring mission progress, ready to step-in, if necessary, to correct mission or abort it.

On the other hand, humans are the most common factor of failure, due to their nature.

The drone operator is frequently named as UAVO (UAV Operator), regardless of the flight nature (autonomous, fully manual, VLOS/BVLOS/FPV).

Aviation learned the lecture and introduced tight verification system, based on procedures that are updated on every air catastrophe or even slight incident reported, to avoid such situations in the feature. Thanks to this approach, aviation became the safest travelling method (well, almost, lifts seem to be safer, anyway). Drones are naturally sharing part of the aviation world, but on the other hand, freedom of purchase, mass scale of the operations (mostly RC, unregistered) is naturally so much different than the hermetic world of pilots and ground staff.

Anyway, many of the rules, hints and regulations, as well as good practices for airmen can be adapted for UAVOs, directly wor with slight modifications.
Below we consider human limitations and some of the good practices for UAV operations.

10.11.1. UAVO

Starting a career as UAVO is somehow like learning, how do drive. In the beginning, operations seem to be magic and bit scary, along with the growing experience they become natural and then switch to the routine. And the routine leads to mistakes.
In aviation, there is a known phenomena, so-called "dead zone", where new pilot starts to operate on his own. Most of the flight accidents and incidents happen between 50 and 350 flight hours. Similar phenomena apply to the UAVOs but exact flight experience time is under investigation. Once UAVO gets used to fly, there appear shortcuts in operation preparation and that lead to accidents. While many UAV accidents are not deadly and most of them finish with hardware damage only, some may cause serious effects on 3rd parties, not only the wallet. Drone operations are not so strictly described as in case of the plane operations but this tends to change, i.e. along with the introduction of the standard and non-standard scenarios for drone operations, as standardised across UE (the details are present in the drone regulations chapter.
Because drone operations can interact with other airspace users, it is common that UAVOs require professional certification, regarding operation place and drone MTOM (Maximum Take-Off Mass). It is common that devices below 250g are considered as toys, and those equal and above may require certification to operate, regarding operation location, altitude and many other factors. Keep in mind that EU standardisation is a process at the moment of writing this manual and local regulations may vary.

10.11.1.1. Model SHELL

One of the best known conceptual models of the human factors related to the aviation (and thus drone operations to some extent) is the so-called SHELL model. It was introduced by Elwyn Edwards in 1972 and is composed of the following components:

- Software: should not be understood as computer software only, but also instructions, aviation regulations, policies, procedures, customs as well as habits and practices.
- Hardware: all physical components that constitute the UAV ecosystem.
- Environment: operational environment, including physical factors like air pressure, humidity, clouds, fog, etc.
- Liveware that is a human component of the model (here UAVO), their limitations performance and capabilities.

10.11.2. Human nature

Human-operator due to its nature is limited. Knowing the limits is essential for understanding operation challenges and avoiding unnecessary risk, eventually handling it properly.
Following limitations are to be considered when getting ready for operation:

- Tiredness: impacts both operation preparation as well as handling of the operation-it causes low focus.
- Mood: anxiety, low mood impacts strongly focus and emotionless approach to critical situation handling.
- Diet: inappropriate diet may cause lack of concentration, i.e. use of too much caffeine.
- Drugs: as in the case of driving, flying a drone while using narcotics and alcohol is strictly forbidden in most countries.
- Sight: in the case of the VLOS operations, being able to observe drone is necessary. This limits ability to position drone in 3D space and also determines operation range.
- Experience: being experienced UAVO is usually an advantage but there is a risk of drifting towards shortcuts as discussed above.
- Illness: some diseases exclude being a UAVO at all, while others limit operation class and MTOM category: i.e. diabetes, heart diseases and so on.
- Environment: the presence of other people and related disturbances may impact focus.

It is also worth to mention, that the human brain has limited perception capabilities, i.e. a need to stabilise a quadcopter at least 100x per second (usually much faster), disables direct motor control. Because of it, every multirotor requires an FC, that performs platform stabilisation autonomously and without FC, a human cannot control motors it directly.

Statistics are inexorable: around 80% of the accidents/incidents are caused by the human factor.

10.11.3. Updateability trap

Most of the drones and related infrastructure nowadays brings the capability to update their software (firmware). As it is not common, sometimes developers introduce new features that impact behaviour and user interface. For this reason, it is strongly not advised to update drone firmware/software right before the operation, but rather to do it in a spare time and give it necessary testing, to avoid surprises.

Regarding open-source FC firmware, the common situation is a requirement to reset all settings, once updated with major revision. That simply means each drone construction have to be re-configured with care after each update and all functions and procedures should be checked.

10.11.4. Meaning of procedures

Aviation is considered to be safe, because of the procedures, strictly and precisely describing each operation. A similar approach is being introduced in the drone operations, so many certified UAVOs keep procedure charts to refer to it.
Those procedures are in short describing three main stages of the drone operation:

- Before the operation: everything, starting from planning, prior take-off;
- During the operation: includes also handling of the critical situations;
- After the operation: everything, starting right after landing, until the operation is finished; This may include also data processing, if necessary.

Each stage should be carefully prepared and tailored to the particular components, including (among others) drone, ground station, communication and remote control. It is common to have paper or electronic checklists, describing carefully each step of the particular procedure, the similar way the pilots do a check-lists. In the case of the UAVO, it is uncommon that procedure checklist is being processed by two persons (as in the case of the passenger planes), as most UAVOs work single. Some basic approach to the procedures can be found on the Internet and they are also provided by drone manufacturer, along with the device purchased.

10.12. Regulations on UAV Operations

10.12.1. Overview of the EU UAV Regulations

New EU regulations for using civil drones are prepared to be published in the summer of 2019. It will take one year to implement these new rules in all EU countries. The new regulations aim to create a level playing field in Europe and will remove drone operations from the aviation domain in terms of regulation. Current manned aviation regulations are rule-based and have proven to be insufficiently flexible for the rapid changing drone market.

The new regulations divide the operations to the **commercial** and **recreational** which are risk-based, assigned them into the **low-risk category** (open category) and a **medium-risk category** (specific category). The **high-risk operations** will remain in the (manned) aviation domain under the certified category (which is currently not addressed in the new regulations).

The open category places very few demands on the pilot or operator and implies a buy-and-fly approach. Pilot qualification can be as simple as an online exam. The drones themselves will need to have a European approved product certification (CE marking).

Current commercial drone operations will be possible in this open category as long as they do not take place over or near (30m) people. This will imply a heavy influx of companies of all EU member states wanting to use drones as a tool (rather than drone centric service operators).

All other operations, unless high risk, are performed in the specific category. For this category, a risk assessment must be carried out by the operator with associated mitigation measures implemented, and approval requested from their National aviation authority.

Regulations are addressed to the people who are hobbyists or drone professionals and are expected to be published between May and July of 2019. The aim of the new regulatory framework is to standardise the operational regulations in Europe and create a common market.

The responsibility for the operation of civil drones in European airspace below 150 kg MTOM (**M**aximum **T**ake **O**ff **M**ass) was transferred from the National aviation authorities to the European Commission on the 7thof December 2018.

Civil drones refer to all drone usage other than by the military, police or emergency services. They, therefore, range from hobbyists operating a DJI Mavic to cargo delivery.

EASA (**E**uropean Union **A**viation **S**afety **A**gency) has been appointed by the European Parliament to propose to the European Commission the technical expertise to regulate drones below a maximum take-off mass of 150 kg.

The proposed regulations by EASA have been unanimously accepted by the European Commission on the 28th of February 2019. These regulations are called the **Implementing Act** and are accompanied by the **Delegated Act** that was adopted by the European Commission on the 12th of March 2019.

The **Implementing Act** consists of two documents, the **Commission Implementing Regulations** and the **Annex** to the regulations. These set out amongst others the following:

1) Different (sub)categories of UAV operations,
2) Rules, procedures, competency and the minimum age for pilots,
3) Airworthiness requirements for the UAV,
4) Cross border operations,
5) Registration of UAV operators,
6) Tasks and designation of competent authorities.

The **Delegated Act** also contains two documents, the **Commission Delegated Regulation** and the **Annex** to the regulations. The delegated regulations cover amongst others the following:

1) CE and operator markings on a UAV,
2) Technical requirements per UAV category,
3) Obligations of manufacturers, importers and distributors of UAV,
4) Requirements on non-EU country operators,
5) Remote identification.

Between May and July of 2019, the new regulations will be published. The national CAA's then have one year to implement these regulations before these come into force in July 2020. Up until that date, it is still possible to operate under the current regulations and even apply for a permit/exemption based on these regulations. From July 2020 onward it is still possible to use previously obtained permits and exemptions for a period of two years up to July 2022. From then on it is only the EU regulations that are applicable.

10.12.2. The EU Regulations

The new European Regulations will have an impact on the whole drone industry. The main gain is that it creates a European wide structure and uniformity in comparison to the current shattered and incomprehensible regulations that differ in each country. The regulations also give UAV pilots more privileges than in the past.

Local Civil Aviation Authorities still have some say in matters such as designating no fly zones or creating special zones with specific regulations. However, the implementing act prevails over local regulations meaning that individual CAA’s cannot make the rules stricter.

The main change is that the new regulations are risk-based. This means that the risks of each type of operation and with different types of drones are evaluated. For example, flying a heavy drone over a populated area carries a far greater risk than flying a little hobby drone in a remote area. Only the location matters, i.e. where drone flights will be relevant but not what they are doing.

Other main principles in the new regulations are:

1) Rules are made at European Level,
2) Implementation is done at national level,
3) No differentiation between commercial or recreational use,
4) Regulations are a mix of product specifications and aviation regulations,
5) Drones in the open category must be CE certified (with the exception of self-build drones),
6) Drones will be partially removed from strict aviation regulations in most countries,
7) Operators can be natural persons as well as legal entities,

The product specifications for drones have been introduced since technical developments of drones have progressed in such a rapid pace that legislation was no longer able to keep up. At present, a new model drone replaces the earlier version at an average rate of 9 months comparing this to manned aviation where this cycle takes around 7 to 9 years.

Under the new regulations, drone operations in the EU are subdivided into three categories:

1) In the **open category**, operations can take place that is considered low risk and does not require prior authorisation.
2) In the **specific category**, operations take place that considering the risks require authorisation by a competent authority before the operation takes place. A risk assessment must be carried out and mitigation measures identified unless the operation is very common. In the latter case, the risk assessment and mitigation measures have been previously identified and part of a ‘standard scenario’ which is approved by EASA.
3) In the **certified category** operations take place that considering the risks require a certified drone, a licensed pilot and an organisation approved by a competent authority to ensure an appropriate level of safety.

The current proposed regulations do not cover the certified category. In this category, the drones will have to comply with standard aviation requirements and the operational rules are the same as for manned aviation.

The regulations provide more freedom for the UAV operator in the fact that certain aspects have not been made explicit in the new regulations. For example, most countries in Europe would define VLOS (Visual Line Of Sight) as the distance to which the UAV can be seen but to a maximum of 500 meters. This is also the maximum distance from the pilot that a drone can currently be flown under most European Regulations at present. But this 500-meter limit is not present in the new regulations. If the UAV can be seen at 1,500 meters distance, it can be used free. The other important fact is that the regulations do not address drones as remotely piloted aircraft but as unmanned aircraft. In the new regulations an autonomous flight will be permitted as the drone is not remotely piloted (with the exception of subcategory C4 in the open category).

Last but not least, the main identified risk factor is flights over – or near – people. Buildings are not addressed, and this offers further opportunities to operate in dense urban areas.

10.12.3. OPEN CATEGORY

The Open Category is meant for low-risk operations whereby no prior authorisation is required. Depending on the subcategory it can be as simple as '**Buy and Fly**'.

This category caters for all recreational drone users as well as for some commercial drone activities. The Open Category is subdivided into three subcategories that stipulate the use of a specific type of drone, whether the drone is to be registered, needs electronic ID, and the pilot requirements. The table below shows a simplified version of the subcategories.

Table 7: Subcategories in the Open Category

Subcategory	Description	Drone Class	MTOM	Pilot Skills	Tech. Requirements	Electronic Id	Operator Registration
A1 Over people	Uninvolved people but not crowds	C0	<250 g	None	< 19 m/s, Max Height	No	No
		C1	<900 g	Online training, Online tests	< 19 m/s, Max Height, Fail Safe	No	Yes
A2 Close to people	At a safe distance from uninvolved people	C2	< 4 kg	Online training, Online tests, Theoretical Test	Max Height, Fail Safe	Yes/SN	Yes
A3 Far from people	Safe distance from urban areas	C3	< 25 kg	Online training, Online tests	Max height, Fail Safe	Yes/SN	Yes
		C4			No Automatic Flight	If required	Yes

So, for example, if a drone operator wants to fly over uninvolved people this will mean that he can operate in the **Open Category**, but only with a drone that weighs less than 900 g. If drone operator wants to fly over people with a DJI Matrice 600 (MTOM > 7kg) then this operation would automatically fall into the **Specific Category**.

Table 8: Technical specifications in the Open Category

C0	C1	C2	C3	C4
Toy	DJI Spark/Mavic	DJI Phantom/Inspire	DJI M210/M600	Model Aircraft
< 250 g	< 900 g	< 4 kg	< 25 kg	
Max speed 19 m/s	n/a	Low Speed max 3 m/s	n/a	Not autonomus
n/a	Unique SN required			n/a
Deviation possible	Fire proof marking of registration			Deviation possible
n/a	E-identification and Geo-awareness (geofencing) required)			In specific areas
n/a		Data link protection required		n/a

C0	C1	C2	C3	C4
n/a		Lighting required		n/a
n/a	Registration required (national responsibility)			n/a
Manufacturer to supply safety leaflet and product information				

Market Product Legislation (better known as CE markings) will be required for all drones operating in the open category and will demonstrate compliance with the technical specifications. The CE marking and the subcategory must be clearly marked on the drone. A certificate of airworthiness is not a requirement for the open category.

However, this CE marking is not mandatory until at least July 2022 and even then, there will most likely be a transition phase whereby drones produced before will not yet have to be CE certified.

The exact details of the pilot training, who should examine them or how to register a drone, are all unclear at present. The following (operational) issues are already clear:

1) The previous distinction between recreational and professional use of drones is removed.
2) The maximum height limit is set at 120 m.
3) The safe distance from people is a minimum of 5 metres (if the drone is equipped with a low-speed mode, otherwise it's 30 meters) and equal to the height at which the drone is flown (1:1 rule).
4) Minimum age is 16.

10.12.4. SPECIFIC CATEGORY

The 'specific' category is for all operations that do not comply with the limits of the 'open' category. In this category, a risk assessment must be carried out for each and every operation, and mitigation measures must be identified and adopted. The outcome of the risk assessment must be authorised by the CAA of the member state.

To assess risks a standard methodology has been devised by **JARUS** (**J**oint **A**uthority for **R**ulemaking on Unmanned Systems). **JARUS** is a group of experts from **National Civil Aviation Authorities** worldwide that make recommendations on technical, operational and safety requirements for the safe integration of drones into the manned airspace. This methodology is called the **SORA** (**S**pecific **O**peration **R**isk **A**ssessment).

The **SORA** methodology divides the risk of a drone operation into two distinct classes:

1) **Air Risk**: the risk of a collision between the drone and another airspace user.
2) **Ground Risk**: the risk of collision of the drone with people, animals or objects on the ground.

For any operation that is not covered by a standard scenario, the operator must conduct the full (SORA) risk assessment and obtain permission from the CAA to go ahead with the operation.

Besides conducting the **SORA** risk assessment, or using a standard scenario, there is a third way in how an operator can qualify for an operation in the specific category. This is through the process of obtaining the **Light UAS Operator Certificate** (LUC). A LUC qualified operator is allowed to assess the risks themselves and implement their own mitigation measures. Obtaining the LUC will not be an easy matter and cannot be compared to any existing permit in Europe.

10.12.5. European Institutions and Rule Making

All EU member states are sovereign, independent countries but they have pooled their sovereignty on some matters to obtain benefits of size. At the heart of the EU decision making process are the EU institutions such as the **Parliament**(voted directly by all citizens), **the EU Commission** (EU government with one member per Member State) and the **European Council** (heads of state of each country). Generally, the European Commission proposes new laws and the Parliament, and the Council adopts these new laws. This means that both Parliament and the Council must agree independently to these new laws, after which the Member States and implements them. In practice this means that if neither the Council or Parliament object within a two-month time frame, the new EU regulations on drone operations will be published in 2019.

Legal Acts of the EU are laws which are adopted by the institutions of the EU and come in various forms. A **regulation** is a law that is binding for all Member States. A **directive** is a law that binds the Member States to achieve a particular objective. A **recommendation** or **opinion** has no binding force.

The new drone regulations are found in the **Implementing and Delegated Act**. This is a European invention to simplify the system of rulemaking by separating the 'legislative' (Delegated Acts) from its executive aspects (Implementing Acts).

In dummy terms, the implementing act is more political and describes the regulation on broader terms and on the 'how'. The delegated act comes closer to real rulemaking and describes the 'what' of the regulation as laid out in the implementing act. The regulations in the delegated act come directly from the European Commission. <caption>EU acceptation for UAV rules timeline</caption>

10.13. Polish Civil Aviation Authority Drones Regulations

10.13.1. Recreational or Sport Drones flights

1) Drone operator which wants to fly drones for fun or sports competitions can use it:
2) without a UAVO certificate of qualification,
3) within visual line of sight,
4) in FPV if the drone does not exceed 2kg,
5) without aero-medical examinations,

The drone operator is responsible to take extreme caution due to the air traffic safety and public order.

10.13.2. General rules for recreational drone flights

In case if the weight of the UAV doesn't exceed the weight of 600g operator must maintain a safe distance from cities, settlements or concentration of people in the open air. This distance isn't defined in meters. The operator decides what distance is safe for equipment which is in use to fly.

If the **UAV exceeds 600g** the drone operator must follow the rules:

1) maintain a horizontal distance of not less than 100 m from the buildings of towns, cities, settlements or gatherings of people in the open air (operator can fly in the city if he finds enough space);
2) maintain a horizontal distance of not less than 30 m from people, vehicles or constructions l (UAV should not fly directly over people).

Regardless of the weight of the drone or UAV model, the operator should also follow rules: Operator or assisting person should constantly keep eye contact with the drone or model, so that it can easily determine its flight and, if necessary, avoid collision with other airspace objects or obstacles. The operator may temporarily lose eye contact with the drone or model when checking flight parameters transmitted by equipment being a drone or flying model equipment;

If the UAV is equipped with a camera (FPV) and there is nobody who can observe the drone or model in the flight, it is restricted not to fly:

1) higher than 50 m above ground level,
2) at a horizontal distance of more than 200 m from each other,
3) at a distance of fewer than 100 m from the building or from gatherings of people in the open air.

In the Polish airspace are such places where UAV can't fly for safety reasons or operator must obtain a special clearance for a flight in a given zone. To easily check where UAV can fly or not, on the **Polish Air Navigation Services Agency** (PANSA) website is available application to download which shows these zones which are restricted. Some regulations where UAV are restricted to fly are listed below:

1) Airports, firing ranges and military units,
2) Prohibited Area (P) – the UAV flights are permitted only with the clearance provided by the prohibited area operator and under conditions defined by the operator,
3) Control Zone (CTR) and Aerodrome Traffic Zone (ATZ) – UAV flights only under conditions specified by the air traffic service provider or with the clearance of CTR or ATZ operator and under conditions defined by the operator. The operator doesn't need clearance in cases:
   - for flights within visual line of sight (VLOS) with drones or flying models weighing not more than 25 kg at a distance of more than 6 km from the airport boundary and up to 100 m above ground level;
   - for flights within visual line of sight (VLOS) with drones or flying models weighing less than 600 g at a distance of less than 1 km from the airport boundary and not higher than 30 m or up to the highest obstacle, including trees or buildings within a radius of up to 100 m from UAV,
4) Danger Area (D) – UAV only fly with the clearance of the danger area operator and under conditions defined by the operator;
5) Military Control Area (MCTR) – UAV can only fly with the clearance of the MCTR operator and under conditions defined by the operator;
6) Military Aerodrome Traffic Zone(MATZ) – UAV can only fly with the clearance of the MATZ operator and under conditions defined by the operator;
7) Restricted Area (R) – in case of drones and flying models, this is the area covering the airspace located directly over the national park where drones can fly with the clearance of the operator of the given national park and under conditions defined by the operator;
8) Air Defense Identification Zone (ADIZ) – this zone is located along the entire eastern border of Poland. In this zone, drones can fly after notifying their location and time of flight to air traffic service (ATS) unit responsible for the airspace in which the flight is to be performed, or to AMC Polska (Airspace Management Cell of the Polish Air Navigation Services Agency).

10.13.3. Flights other than recreational or sports flights with visual line of sight (VLOS)

If the drone is flying for purposes other than recreation or sport (e.g. use for the business using the unmanned aerial vehicle UAV), the drone operator must operate as a UAV operator.

General conditions and rules of flights The drone operator must obtain a "certificate of qualification of unmanned aerial vehicle operator (UAVO)" used for purposes other than recreation or sport with a rating to perform VLOS operations (it also entitled to limited FPV flights). This document is issued by the President of the Civil Aviation Authority (CAA). UAV operator will receive it after completing a special training course and passing the necessary exams. If the operator is under 18 then he will need the consent of his legal guardians to obtain a certificate of qualification. He will need also to fly under the supervision of an adult. One of the conditions is also having appropriate third party liability insurance.

Aero-medical examination If the UAV is heavier than 5 kg, the drone operator must also need to obtain the appropriate aero-medical examinations.

Responsibility First of all, when flying, the operator is responsible for exercising extreme caution due to air traffic safety and peace and public order. The flying equipment must be technically efficient. The operator is responsible for the safe and lawful use of an unmanned aircraft.

10.13.4. Rules of VLOS and FPV flight

In **VLOS** operations:

- The operator must maintain a safe distance from aircraft, buildings, gatherings of persons in the open air as well as from persons, vehicles and constructions which are not under operator control in each phase of flight. The safe distance is not determined by the rules in meters. The operator decides what distance is necessary for the UAV flight not hurt anyone;
- Operator or at least one observer should keep eye contact (with the unaided eye) with UAV in order to determine its location in the airspace and ensure a safe distance from other aircraft, obstacles, people or animals. In VLOS operations operator may temporarily lose eye contact with UAV when checking flight parameters transmitted by equipment being a UAV ground equipment.

In **FPV** operations:

- UAV with a maximum take-off weight of 2 kg;
- up to a height of not more than 50 m above the ground level;
- at a horizontal distance of not more than 200 m from the operator;
- at a horizontal distance of not less than 100 m from the buildings of towns, cities, settlements or gatherings of people in the open air.

In **VLOS** and **FPV** operations:

- providing full flight control, in particular by remote control using radio waves,
- taking into account the meteorological conditions, structure and classification of airspace as well as information on air traffic limitations,
- in CTR: under conditions specified by the air traffic service provider,
- in ATZ: with the clearance of the ATZ operator and under conditions specified by the operator,
- in Danger Area, MCTR or MATZ: only as cleared and needed by the area/zone operator and under conditions specified by the operator,
- in Restricted Area covering the airspace located directly over the area of the national park the drone can fly with the clearance of the operator of the given national park and under conditions defined by the operator,
- in EP R40 Słupsk: only the aircraft referred to in Article VII para. 3 of the Implementing Agreement between the Government of the Republic of Poland and the Government of the United States of America to the Agreement between the Government of the Republic of Poland and the Government of the United States of America concerning the deployment of ballistic missile defense system in the territory of the Republic of Poland regarding use of land areas and airspace surrounding the ballistic missile defense system base, signed in Warsaw on 27 April 2015 (Journal of Laws of 2016, item 234), upon approval referred to in this provision,
- in Prohibited Area: only as cleared and needed by the area operator and under conditions specified by the operator,
- in ADIZ: after notifying drone location and time of flight to air traffic service (ATS) unit responsible for the airspace in which the flight is to be performed, or to AMC Polska (Airspace Management Cell of the Polish Air Navigation Services Agency),
- in case of flights within building structures: as cleared by the facility operator and in accordance with agreed safety rules,
- flights performed over:
  - closed areas;
  - nuclear facilities;

- ➢ areas, facilities and devices referred to in Article 5 para. 2, point 1, letter a and b, point 2. letter a and b and point 3, letter a and b of the Act of 22 August 1997 on the protection of people and property (Journal of Laws of 2018, item 2142),
  - ➢ military units and firing ranges,
- can be performed only as cleared and needed by the area/facility/device operator.
- flights over fuel pipelines, power lines and telecommunications lines, water dams and locks and other devices located in an open area, the destruction or damage of which may endanger human life or health, the environment or cause serious material damage, is carried out with extreme caution;
- operations in CTR, ATZ, ADIZ and Prohibited areas may be performed by UAVs with a mass not exceeding 600 g in VLOS conditions without issuing clearances by the operator under conditions specified above, when flying at a distance of more than 1 km from the airport boundary or 500 m from the site protected by the Prohibited area and up to 30 m or up to the highest obstacle, including trees or building structures, within a radius of up to 100 m from the operator;
- operations in CTR and ATZ may be performed by UAVs with a mass not exceeding 25 kg in VLOS conditions without issuing clearances by the operator under conditions specified above when flying at a distance of more than 6 km from the airport boundary and up to 100 m above the level area.

10.13.5. UAV operation rules

In addition to the requirements concerning flight rules and operators' ratings, regulations also specify obligations of entities operating UAVs:

1) the entity operating a UAV is obliged to:
   - ➢ label all equipment with a nameplate containing the name of the entity owning the unmanned aircraft,
   - ➢ include preventive recommendations of the Civil Aviation Authority (CAA), if issued, in the operations manual,
2) UAVs used for flights earlier than 30 minutes before sunrise and later than 30 minutes after sunset must be fitted with a warning light mounted in a manner that provides an omnidirectional light distribution, visible from above and below;
3) UAV must be fitted with a "failsafe" system programmed in a manner consistent with the CAA preventive recommendations if issued;
4) the operator performing the flight is required to wear a warning vest;
5) an entity providing aerial services using unmanned aircraft must develop an Operational Manual which:
   - ➢ defines a safe way to provide aerial services and includes in particular:
   - ➢ data of the entity providing services,
   - ➢ list of operated UAVs,
   - ➢ personnel data indicating their ratings,
   - ➢ process of risk analysis of air operations in relation to operate UAVs,
   - ➢ list of control activities carried out before take-off and after landing,
   - ➢ procedures and principles of performing air operations,
   - ➢ emergency procedures,
   - ➢ is subject of review if requested by the President of the Civil Aviation Authority,
   - ➢ is supplemented and amended in the manner necessary to keep it up to date,
   - ➢ takes into account preventive recommendations of the President of the Civil Aviation Office issued on the basis of Article 21 para. 2, point 15, letter c of the Aviation Law Act.

10.13.6. Flights other than recreational or sports flights beyond visual line of sight (BVLOS)

If the drone operator is flying an unmanned aerial vehicle (UAV) for purposes other than recreation or sport (e.g. you run a business using UAV or use it as part of its job) and plan to use it in BVLOS operations, he must follow rules as a UAV operator.

Types of flights that can be carried out BVLOS flights, which can be performed as part of the clearance obtained in compliance with applicable regulations are divided into several categories, which differ in terms of the scope of requirements that must be fulfilled to be carried out. These are operational, specialized, automatic and training flights:

1) operational flights are carried out as part of or for the purposes of activities:
   - of state aviation (armed forces, police, border guard, state fire-fighting service),
   - of customs-tax service,
   - related to preventing or combating natural disasters or catastrophes,
   - related to health care systems,
   - related to search or rescue,
   - related to the protection of the internal security of the state,
   - related to the recognition of safety hazards and environmental protection.
2) specialized flights are carried out as part of or for the purposes of:
   - supervision, monitoring, control or protection of land or water civil engineering works, forest or water areas, people or property,
   - geodetic activities related to agriculture or forestry,
   - research, test, trial or demonstration flights.
3) automatic flights are carried out as part of or for the purposes of:
   - supervision, monitoring, control or protection of land or water civil engineering works, forest or water areas,
   - agro-aerial activities,
   - medical supplies,
   - research, test, trial or demonstration flights.
4) training flights are carried out as part of the training activities referred to in Article 95a of the Aviation Law Act.

Clearance to perform operations It should be remembered that operational, specialized, automatic and training flights can be performed only by authorized entities which received clearance of the President of the Civil Aviation Authority. Clearance may be granted only after meeting the requirements by the requesting entity and by the unmanned aircraft that will be used as part of the clearance.

Obtaining clearance for operational, specialized, automatic and training lights - requirements related to unmanned aerial vehicles.

The issuance of clearance referred to above is dependent on the appropriate UAV equipment, which is as follows:

1) in case of a UAV is an aeroplane, it shall be equipped with:
   - green continuous light, placed on the right-wing, visible above and below the horizontal plane of the wing;
   - red continuous light, located on the left-wing, visible above and below the horizontal plane of the wing;
   - white flashing light placed on the top of a vertical stabilizer or, in the absence thereof, on the upper surface of the hull in a manner ensuring an omnidirectional light distribution.
2) in case of an unmanned aerial vehicle being a multirotor, helicopter or aerostat, it shall be equipped with white flashing light, placed on the upper surface of the hull in a manner

ensuring an omnidirectional light distribution;

3. each UAV used in BVLOS operations should be equipped with devices or systems mounted on board or being its ground equipment, to enable:
   - preservation of assumed flight parameters;
   - ongoing monitoring of flight parameters, including the definition of the flight path, flight speed, flight altitude using a barometric altimeter, the degree of battery charging or the degree of fuel consumption, quality and power of the communication signal between unmanned aerial vehicle and remote control station;
   - basic location – determination of current location, speed, altitude and direction of UAV flight in order to transfer these data to air traffic service provider via CIS system or by telephone as requested by ATS unit;
   - emergency location – the operator's determination of UAV current position in the event of irretrievable loss of UAV control capabilities or the occurrence of communication breaks between the UAV control station and the UAV;
   - automatic execution of an emergency procedure, including flight termination by emergency landing, or continuing a flight on a pre-programmed route, or on arrival to a pre-programmed location;
   - recording of flight parameters from the moment when the UAV control system is started until the system is turned off;
4. UAV should also be equipped with a camera allowing observation of its surroundings in order to reduce the risk of collision with another aircraft or obstacle.

Requirements related to the entity performing flights Each entity performing operational, specialized, training and automatic flights are obliged to have and use an operational manual which is constantly updated, takes into account preventive recommendations of the * President of the Civil Aviation Authority and is made in Polish or English. The manual must contain the following elements:

- name and address of the registered office of the entity providing aerial services, its telephone number, e-mail address, tax identification number (NIP) or number in another register in which the entity was registered;
- a list of unmanned aerial vehicles used, including their identification marks;
- first and last name, number of the certificate of qualification and validity date of liability insurance of the operator performing or supervising the flight;
- assessment and information on the method of limiting the risk of flight operations;
- the general list of control activities carried out before takeoff and after landing;
- procedures and rules for performing air operations;
- general emergency procedures;
- procedure for providing inspections of UAV technical condition.

In addition, every operator performing flights are required to wear a warning vest while performing air operations. If the operator is not in an open area, it should be clearly indicated where he is located.

Obtaining clearance Clearance for operational, specialized, training and automatic flights is obtained at the request of the entity that intends to perform such flights.

Clearance is issued after the President of the Civil Aviation Authority verified that the entity meets the requirements concerning operations manual, personnel qualifications, insurance and UAV equipment required by the regulations. Clearance is issued for a period of 12 months.

The President of the Civil Aviation Authority notifies PANSA about entities that have obtained clearance to perform operational, specialized, automatic and training flights. Information is provided within two working days from the date the clearance is issued by the President of the Civil Aviation Authority.

Flight conditions The basic condition that must be met to perform the operations described above is the notification of the willingness to perform a flight to PANSA and publication by the Agency, information on UAV planned and implemented flights. Without fulfilment of these conditions, the flight cannot take place.

The entity wishing to perform a flight informs PANSA about its intention to perform the flight at least 7 days before the date of the flight. Then PANSA publishes information about:

1) UAV planned flights:
   - at least 2 days before the flight date – in case of operational, specialized, automatic and training flights;
   - on the day of flights – in case of operational flights, if it was not possible to plan the flight earlier.
2) UAV performed flights providing:
   - the route of the flight or the area in which the flight will take place;
   - flight altitude above mean sea level (AMSL) along the entire route or on individual sections of the route;
   - flight time planned by the operator;
   - UAV identification mark.

Both the entity submitting to PANSA the desire to perform the flight and the Agency itself will use communication and information system or electronic communication means (e-mail, website or special application), as indicated by PANSA, to communicate between themselves and to publish flight information.

PANSA will issue flight conditions and publish information on their implementation only in the case of entities that have previously received clearance of the President of the Civil Aviation Authority to perform BVLOS operations.

Flight performance Once the flight information has been published, the operations must be carried out under the following conditions and rules:

1) taking into account the comments provided by PANSA regarding the route and the area in which the flight will take place,
2) operational, specialized or training flights,
   - up to not more than 120 m above ground level,
   - at a speed of not more than 150 km/h.
3) automatic flights,
   - up to 50 m above ground level or up to 50 m above the highest obstacle within a radius of 100 m from the place of flight,
   - at a horizontal distance of fewer than 100 m from buildings of towns, cities or settlements under permission and conditions specified by town/city authorities,
   - at a speed of not more than 150 km/h.
4) training flights at a horizontal distance of at least 150 m from housing estates and other population centres and at a horizontal distance of not more than 500 m from the operator performing the flight,
5) ensuring full flight control,
6) at a safe distance from other aircraft, obstacles, persons or animals, taking into account the meteorological conditions and information on air traffic restrictions,
7) in CTR: under conditions specified by PANSA,
8) in ATZ: under clearance and conditions specified by ATZ operator,
9) in Danger Area, MCTR or MATZ: only as cleared and needed by area/zone operator and under conditions specified by the operator,
10) in Prohibited Area: under clearance and conditions specified by the area operator,
11) in Restricted Area covering the airspace located directly over the area of the national park, under clearance and conditions specified the operator of a given national park,

1) in EP R40 Słupsk: only the aircraft referred to in Article VII para 3 of the Implementing Agreement between the Government of the Republic of Poland and the Government of the United States of America to the Agreement between the Government of the Republic of Poland and the Government of the United States of America concerning the deployment of ballistic missile defense system in the territory of the Republic of Poland regarding use of land areas and airspace surrounding the ballistic missile defense system base, signed in Warsaw on 27 April 2015 (Journal of Laws of 2016, item 234), upon approval referred to in this provision,
2) in ADIZ: after notifying your location and time of flight to air traffic service (ATS) unit responsible for the airspace in which the flight is to be performed, or to AMC Polska (Airspace Management Cell of the Polish Air Navigation Services Agency),
3) in case of flights within building structures: as cleared by the facility operator and in accordance with agreed safety rules,
4) In addition, flights performed over:
   - closed areas,
   - nuclear facilities,
   - areas, facilities and devices referred to in Article 5 para. 2, point 1 letter a and b, point 2, letter a and b and point 3, letter a and b of the Act of 22 August 1997 on the protection of people and property (Journal of Laws of 2018, item 2142),
   - military units and firing ranges.
5) can be performed only as cleared and needed by the area/facility/device operator,
6) flights over fuel pipelines, power lines and telecommunications lines, water dams and locks and other devices located in an open area, the destruction or damage of which may endanger human life or health, the environment or cause serious material damage, is carried out with extreme caution,
7) in case of flights related to safety and public order, security and defence of the state, protection of the state border, protection of the internal safety of the state or search and rescue, provisions regarding flights in Prohibited and Restricted areas covering airspace immediately above the area of the national park do not apply,

In case of the failure event All technical devices may fail. However, such a situation in the case of UAV may carry a high risk, so in the event of UAV loss of control or UAV loss, the operator must immediately:

1. notify the competent ATS unit by telephone, via electronic communication means of communication and information system, and attempt to regain communication with the UAV;
2. provide the ATS unit with the following information: UAV current location identified by emergency location device, UAV last known location in the event of failure of the emergency location device, time of communication loss, last recorded speed, UAV altitude and heading, expected time to run out of fuel or depletion of power to the propulsion system.

10.14. Latvian Civil Aviation Authority Drones Regulations

10.14.1. General Rules

1) **Maximum flight altitude**: In Latvia, drones are allowed to fly up to a height of 120 meters.
2) **Maximum horizontal distance and FPV**: You should also operate your drone only in visibility (VLOS) in Latvia.
3) **Compulsory insurance**: We recommend you complete an aviation liability coverage for your drone.
4) **Maximum take-off weight (MTOW)**: The maximum weight for unmanned aeroplanes is 20 kg.
5) **Distance to airports**: You have to keep a distance of 10 kilometres to airfields.
6) **Other safe distances**: Your copter must not approach people, animals, vehicles and flammable/explosive objects closer than 50 meters.
7) **Flight bans**: Drone operator is not allowed to fly over the following objects: buildings, bridges, railways, motorways, motorway crossroads, electricity and communications lines,cemeteries, gatherings of people, pilgrimage churches, and military infrastructures. He must maintain a distance of 200 meters.

8) **Regulations for commercial pilots**: As far as today there is no subdivision of private and commercial drone flights in Latvia.

9) **Good to know**: Drones must be able to land autonomously in Latvia in the case of disconnection of the radio link (failsafe function).

According to the new regulations approved by the **Cabinet of Ministers**, drones can be piloted by persons from the age of 16, while flights in heightened risk circumstances can be piloted from the age of 18. Those wishing to fly unmanned aircraft in heightened risk circumstances will also have to obtain a permit from the Civil Aviation Agency. In order to obtain such a permit, the candidate will have to pass a theoretical and practical exam, as well as a flight risk assessment. The theory exam and practical flight tests can be completed free of charge. When the permit is received from the Civil Aviation Agency, it will be possible for persons to fly drones near public events. At the same time, regulations for flying drones near or above infrastructure objects will be made easier. Furthermore, informative signs will be put up in areas where unmanned flights are prohibited. The new rules will also regulate the observations of safe distances, while at the same differentiating the weight of the unmanned aircraft and its speed. The regulations are supplemented by minimum liability limits for civil liability insurance. It will henceforth be extended to unmanned aircraft with a total take-off mass of over 250 grams for high-risk flights. On the other hand, unmanned aircraft with a take-off mass above 1.5 kg will require third party liability insurance regardless of the risk of flight. The regulations impose stricter requirements for the operation of unmanned aircraft near airports, airfields or elsewhere that impose restrictions on the use of airspace. The **Cabinet of Ministers** regulations will come into force in 2019 year after their approval, except for the provisions relating to insurance conditions, the installation of warning signs and flight model flights. The state-owned air traffic controller **Latvijas Gaisa Satiksme** will also draw up aeronautical information for unmanned aircraft, and there will be a transition period until January 2, 2020. The aim of the new regulations is to contribute to the safety and security of unmanned aircraft operations, building on the practice of applying the existing regulatory framework, while taking into account aspects of the common regulatory framework already adopted on the European Union (EU) level.

10.15. Last UAV Operations rules changes in Poland 31 Dec 2020

According to the new European regulations, which are to enter into force in Poland at the end of the year, there will be no obligation to register every drone. However, there will be an obligation to register an unmanned vessel operator. Registration can be made on the website of the Civil Aviation Authority. On December 31, EU regulations and procedures for the operation of unmanned aerial vehicles (UAV) are to enter into force. The European Aviation Safety Agency has decided to unify the rules and procedures for drones in all European Union Member States.The Civil Aviation Authority has developed solutions to improve security and open borders for the unmanned industry in the EU. Therefore, as of **1 January 2021**, the national regulations and procedures of the EU Member States dedicated to civilian drone users will no longer apply.One of the biggest changes will be the lack of distinction between sports or recreational flights and non-sports and recreational flights. The current commercial use of drones - possible only for holders of the UAVO operator qualification certificate - will in most cases become generally available. On the other hand, users who fly purely for fun will be faced with additional obligations that did not apply to them until now. A classification of the flights performed will appear, divided into categories: *open*, *special* and *certified*. The division was made based on the **risk level of the air operations performed**. In the open category, drones weighing less than 25 kg will be able to fly only within sight and up to a height of 120 m. In the special category, consent or declaration is required at the Civil Aviation Authority, and flight conditions are determined based on a risk analysis. Local airspace restrictions may also apply in cities, so it is worth checking them through the website of the Polish Air Navigation Services Agency or a dedicated application. In the open category, any person who wants to fly a drone weighing more than 250g will have to undergo a simple on-line training and pass an on-line test confirming the acquisition of the required theoretical knowledge. An online mandatory registration system will also be created for all users of drones weighing over 250 g.

- There will be no obligation to register every drone, there will be an obligation to register an UAS operating in the **open** and **specific** categories,
- Drone operators will put the registration number on the drones,
- Minors over 14 years of age will be able to register in the Operators Register. To do this, the consent of the legal guardian will be required. In the case of a minor up to 14 years of age, drone operations may be performed by him/her on his own, when the drone is a toy and the flights are performed under the direct supervision of an adult.

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