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# MODELLING AND DESIGN OF NEUROMECHANIC SYSTEMS

Summary. Neuromechanics is defined as an intelligent control of motion of an engineering system which as its objective has generation, conversion and transmission of energy. The concept of neuromechanics is based on the understanding that engineering system generates, processes and transmits generalised information that may be in a form of energy, mass or control information. Neuromechanic systems may be implemented using various available technologies. The implementation of neuromechanics using "smart" electronic and mechanical technologies produces mechatronic systems. The paper describes methodology of design and modelling of a neuromechanic systems.

# MODELOWANIE I PROJEKTOWANIE SYSTEMÓW NEUROMECHANICZNYCH

Streszczenie. Neuromechanika definiowana jako inteligentnie sterowany ruch systemu technicznego, którego celem jest wytwarzanie, przekształcenie i przekazywanie energii, bazuje na rozumieniu, że systemy techniczne wytwarzają i przekształcają uogólnioną informację, która może być generowana w formie energii masy i informacji. To uogólnione pojęcie jest niezależne od rodzaju technologii, która może być zastosowana w takich systemach. Systemy neuromechaniczne mogą być realizowane przy użyciu różnych dostępnych technologii. W szczególnych przypadkach realizacja neuromechanicznych systemów może prowadzić do układów mechatronicznych. Niniejsza praca formułuje metodologię modelowania i projektowania neuromechanicznych systemów.

# МОДЕЛИРОВАНИЕ И ПРОЕКТИРОВАНИЕ НЕЙРОМЕХАНИЧЕСКИХ СИСТЕМ

Резюме. Нейромеханику можна определить как умно управляемое движение, ей целью является произвоводство, превращение и передача энергии. Понятие нейромеханики основывается на мнению, что технические системы создают и превращают обобщенную информацию, которая может быть генерирована в форме энергии, масы и информации. Нейромеханические системы можна реализировать употребляя разные доступные технологии, особенно при применении мехатронических систем. Настоящая работа формулирует методологию моделирования и проектирования нейромеханических систем.

## 1. INTRODUCTION

Current development in electronic and computing technologies as well as rapid development of new engineering materials spurred the development of faster, smarter, efficient engineering systems defined as mechatronic systems which combine these technologies [1]. Although the definition of mechatronics specifically refers to two technologies - mechanics and electronics, new development in control technologies, e.g. fibre optics, laser technology, are also included in the definition.

It appears that there is a need to define this new system not in terms of technology but in terms of the functions they perform. Thus, we define ***neuromechanics*** as an intelligent control of motion (and associated forces) of an engineering system which as its objective has generation, conversion and transmission of energy. It is an abstract concept defining systems with explicit separation of control (neuro-) and power (-mechanics) functions with no specific technologies in mind. The concept of neuromechanics is based on the understanding that an engineering system generates, processes and transmits generalised information that may be in a form of energy, mass or control information. The generality of the concept makes it independent of technologies used in implementation of such systems.

In their most advanced implementation neuromechanic systems provide intelligent control of motion and forces. The intelligence level of the system will depend on control schema - the systems operating in varying, unpredictable environment will have to have a high degree of intelligence. The intelligence level of an advanced neuromechanic system will range from adaptive controls to advanced knowledge processing systems based on fuzzy logic, neural nets, genetic algorithms [2,3].

The systems that use specific technologies, for example mechatronics, belong to a subset of neuromechanics. Most definitions of mechatronics state that it is a technology *integrating* electronic (computer) control with mechanical systems.

A study of the mechatronic devices shows that contrary to these definitions there is, in fact, a very clear *separation* of control and power (mechanical) functions. As the mechanical systems are stripped of their control functions the need to provide information to a control (an electronic) system generated a burgeoning demand for sensors and what, is not so apparent, for transducer converting electronic signals to electrical signals necessary to operate power control devices.

The separation of control from power functions has a direct effect on the intrinsic safety of mechatronic devices and on the future development of mechanical hardware. The mechanical devices can be designed to be intrinsically safe - using mechanical feedback, mechanical safety devices, etc. The safety of mechatronic systems is based on electronic software and/or hardware and electronic interfacing that has not the same degree of intrinsic safety and reliability.

The future progress in development of mechanical components is also uncertain. Why should anyone spend the money to develop, for example, a hydraulic valve that has inherently correct dynamic characteristics, flow force compensation, linearity when we can take an inferior quality valve and by tweaking the electronic control make it appear to have such characteristics. As long as electronics and software work fine all is well. A study of mechatronic literature shows that almost all of the mainstream effort is directed towards development of sensors and control and very little effort is directed towards development of mechanical hardware, although there is some activity in research and development of micromechanical systems.

All control techniques (knowledge based systems, neural nets, fuzzy logic, genetic algorithms) which provide control are still not robust enough to provide required level of safety, thus there are not many implementations of theses control techniques in industrial applications in which safety is critical. In addition, the AI systems have no *metaknowledge (knowledge about knowledge)* which would prevent attempted operation of the system outside its *knowledge* domain. A supervisory, essentially non-intelligent system, for example PID controller, mechanical override is thus necessary to prevent this happening and/or supervision by a human operator .

Monitoring of system condition, the human skills required to service and maintain such systems and most importantly costs of such activities are some of the issues that are scantily discussed in literature. The different technologies used to execute control and power functions obviously require different human skills, diagnostic equipment, servicing equipment. Monopolisation of "knowledge" about the system in the hands of a small number of specialists invariably leads to high cost of maintaining and servicing of new, mechatronic, products like motorcars, washing machines, etc. It will also increase cost of industrial products and processes.

The paper discusses development of the concept of neuromechanic systems based on the functional approach and identification of system structure consisting of control, power and external sub-systems (blocks). The paper also presents the methodology of modelling of neuromechanic systems using power bond graphs technique.

## 2. CONCEPT OF NEUROMECHANIC SYSTEM

A great number of books and papers present procedures and methodologies for design of engineering systems [4,5], and more recently a number of researchers proposed methodologies for design of mechatronic systems [6,7]. Whatever approach one takes, the design process must start with the development of a *power model* of the proposed system. Whenever an engineering problem is investigated, a designer can either investigate the system by direct experimentation on the real system or carry out the investigation on the basis of some type of model. One may argue that even when working directly with a real system, the system can be considered to be a "model" of itself as any experimentation is necessarily limited only to some aspects of behavioural or structural characteristics of the real system. The instant the designer conceptualises the real system, he/she is thinking about a system's model. Thus, modelling activity is basic to the design process and a prerequisite to any design activity, fig. 1.

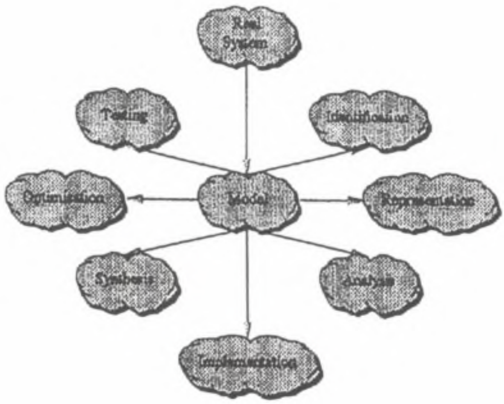



Fig.1. Investigation of the system

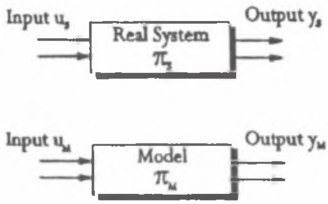
Rys.1. Badanie systemu

The starting point in the discussion is the definition of a system and generalised information. A dictionary definition of a *system* is "a set or assemblage of things connected, associated or interdependent so as to form a complex unity". Implied in this definition is the purpose of such a set which, in engineering terms, is the transmission of *generalised information* that can be in a form of energy, mass or control information. We are interested in mechanical machines, i.e. physical systems whose primary objective is to transmit energy and convert it into useful work. The system has a *boundary* that encloses the system and a number of points that are common with other systems or the environment.

These points are information transfer terminals, and the information passing through these points will define the character of interaction with other systems and the environment. Thus the system can be investigated in isolation from other systems and its environment. Although selection of a system's boundary is arbitrary, the choice of boundary is influenced by the objective of the investigation. The objective of modelling is to construct a system, a model, which is a subset of the real, physical system. Investigation of the model will yield information about behavioural and structural properties of the real system under consideration.

Let us assume that we only have a description of the need, that is a statement of the system's objective and our task is to design the product or system to satisfy this need. A typical example could be an end effector (a mechanical hand) which allows handling of fragile, irregular shape components. The end effector is attached to the manipulator arm that positions the workpiece according to some required program. The first step in considering such a problem would be to identify a boundary that will separate the effector from its environment and to identify its attributes (information transferred to and from the system to the environment). The process of delineation of a system boundary and identification of its attributes is called modelling. The real object has a great number of these attributes and the investigation of the system would be difficult if all are considered, thus a skilful designer will select only these attributes that are relevant to the subject of investigation. To simplify the investigative task some attributes are totally ignored while others are idealised, on the basis of a certain set of criteria and assumptions accepted by the designer. The correct choice of modelling assumptions is the one factor that will usually seriously affect the quality of the system investigation and the magnitude of modelling and simulation tasks. The model of a real system, developed on the basis of such a set of assumptions, should in all important aspects be equivalent to the original real system.

The subset of selected variable attributes of the system that represent information transfer between the environment and the system can be separated into two sets. These variable attributes that represent information transfer from the environment to the system and which can be controlled or manipulated are assigned as *inputs* to the system. Variable attributes that represent information transfer from the system to the environment and can be measured or observed are assigned as *outputs*. Other attributes that represent the physical or geometric attributes of a system, for example kinematic viscosity of fluid, or which cannot be or were chosen not to be controlled and/or manipulated are designated as parameters. Parameters do not have to have constant value, e.g. viscosity of fluid will vary with system temperature. In the case of a new product the model is represented as a **blackbox** as its technological implementation and structure (topography) are as yet unknown. The blackbox power model of the system accepts the inputs, processes them, and transfers the output information to the other systems and/or environment, fig.2.




Modelling

$$u_S \longrightarrow u_M$$

$$\pi_S \longrightarrow \pi_M$$

Fig.2.Blackbox model of system

Rys.2. Czarna skrzynka modelowanego systemu

The action of the system in meeting the system's objective is described in terms of functions that the model (system) must perform to process input information into output information. Identification of functions is rather difficult task but the effort may be greatly reduced by using some of the value analysis techniques like FAST (Function Analysis System Technique), some functions of the effector are shown in fig. 3.

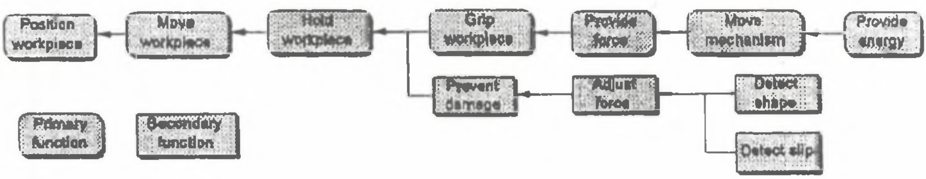



Fig.3.Functional diagram of the gripper

Rys.3. Schemat blokowy działania chwytaka

FAST technique allows identification of primary (basic) functions that *must* be performed to meet the objective of the system and secondary (supporting) functions that, although sometime necessary, do not add to functionality of the system.

Each function should be described using a verb broad enough as not to limit the way the function is performed (*produce* a hole rather than *drill* a hole), and a noun making it a measurable parameter (conduct *current* rather than provide *conductor*). Any product consisting of more than just a single part will have a number of basic functions. The linked tree structure of basic and secondary functions shows the hierarchy of functions and dependency of each function on lower and higher level functions. The higher the function the more abstract it is and the design of a system that performs such function will require a more broadly based and more experienced design team.

The FAST diagram shows a hierarchy of primary functions and we will be able to identify the highest level of function necessary to meet the objective of the system. During synthesis step we design system structure that will perform this and all lower order functions. The decision to develop a system concept using a function at a higher level than the one corresponding to the product objective will require reassessment (enlarging) of the system boundary and expanding the sets of system attributes thus increasing the complexity of the system. On the other hand, entry at a lower functional level will reduce the design task, and in the case of low level functions the design task may be reduced to detailed design.

The synthesis of the system is based on the identification of the system's model and functions that the system must perform and the system concept and later its implementation must be contained in a solution space defined by constraints imposed on the system, with each constraint defining a co-ordinate in a solution space. Identification of constraints is a necessary intermediate task in order to develop system specification. Identification of factors (quantitative constraints) and effects (qualitative constraints) leads to a set of requirements, fig.4.

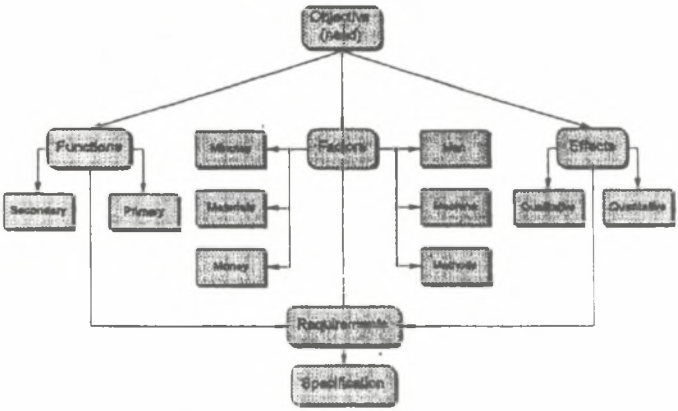



Fig.4,Derivation of specification
Rys.4. Zestawienie specyfikacji

These requirements are in the form of statements such as *car should be economical* or *noise level should be low.* The factors may be identified using mnemonic 6M:

- man(power) - ergonomic factors, skills;
- machine - available tools, production capacity;
- method - production methods;
- materials - corrosion resistance, special materials;
- money - contract price, unit price, transport cost;
- minutes - cycle time.

The effects are defined as qualitative constraints, for example aesthetics, noise, smell. As each function will have a set of constraints thus the solution space will grow as we move up in the function hierarchy. The specification of the system, which is used as a yardstick used to measure the success or failure of design effort, is derived by imposing numerical values on the requirements - e.g. *car fuel economy should be 5 litre per km under city driving conditions with four passengers* or *motor noise level should not exceed 80 dbA at 3000 rpm and load 100 Nm.*

The task of extracting information from the customer and formulating the system's specification is difficult as customer's requirements are often only vaguely defined.

## 3. SYNTHESIS

Synthesis is a process of developing a concept of the system and creating a structure of the *blackbox* model of the system - which will exhibit the specified input/output behaviour and satisfy all functional requirements within the limits imposed by system specification, fig. 5.

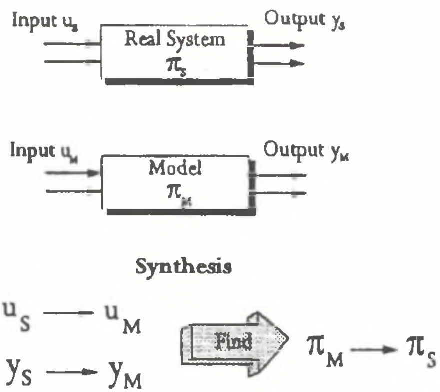



Fig.5.Synthesis Process
Rys.5. Proces syntezy

The structure of the system is represented in symbolic form by a set of engineering documents (technical drawings, circuit diagrams). We propose a structure consisting of power system, control system and external system [8,9], fig.6.

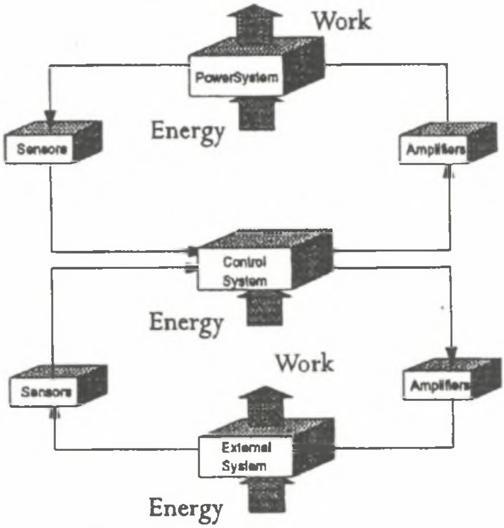



Fig.6. Structure of the system

Rys.6. Struktura systemu

The concept of the *power system* is developed by using a combination of techniques like brainstorming, synetics, etc. and it is concerned only with power functions of the system. For each primary function in turn we are seeking a mechanical, hydraulic, pneumatic or electrical solution. Thus in our example the function *exert force* may be performed by mechanical linkages, pneumatic or hydraulic actuators, electric motors, etc. The proposed solutions are noted on the functional diagram by attaching them to the appropriate function(s). The selection of a particular technology will inevitably cause the appearance of some, additional, supporting functions. For example, the selection of hydraulic technology will be accompanied by supporting functions like pressure compensation, flow force's compensation, leakage control and will also require a supply of a hydraulic power with associated temperature control, contamination control, etc. These functions will usually be assigned to the *external system*.

To satisfy the power objective of the product, it must perform all the primary function, as these functions define energy transfer by the *power system*. The secondary functions may be, depending on their character, arbitrarily assigned to *power system* or to an *external system*. In our example a function *detect irregular shape* is a secondary function and may be either considered to belong to the power system or may be assigned to the external system.

In the latter case we may propose a separate device that will detect the shape of the workpiece and which will be integrated via a control system with the power system.

The external system in itself may be a machine (for example a forging manipulator, robot arm) and thus its structure will consist of power-external-control systems, or a control system (e.g. pressure compensation control). The external system is interfaced with the power system via a control system, thus it provides secondary output control signals to the control system and receives secondary input signals from the control system.

A simplification of a design problem can be obtained by considering the system as a hierarchical structure which in turn leads to a distributed control architecture of the system, fig.7. A designer may arbitrarily or on the basis of some cost, performance criteria assign some parts of the power system to external system thus introducing a hierarchical structure.

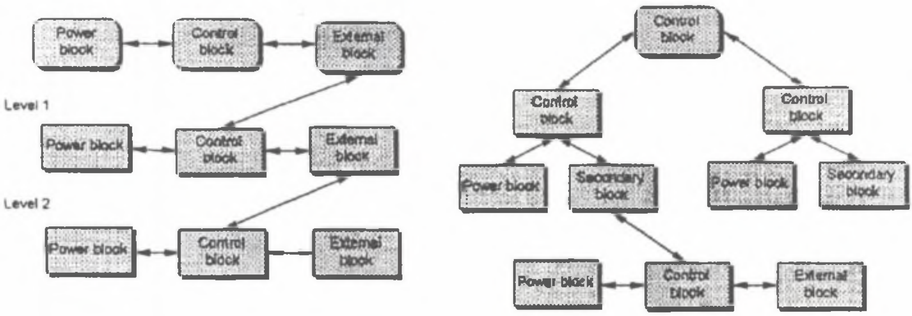



Fig.7. Hierarchical system structures

Rys.7. Hierarchiczny układ struktur

Many systems have a major operating cycle that repeatedly invokes a number of sub-cycles. Usually control systems may be simplified by considering each sub-cycle independently, and then specifying the appropriate interfacing between them. This hierarchical structure of the operating cycle will, in turn, lead to the identification of power and external systems for each hierarchical level. The hierarchical partition of the control functions leads naturally to a distributed architecture of the control system. Looking at the hierarchy of control functions we may observe that a lower level function will probably use traditional control techniques, for example a PID controller, and as we are moving up in control functions hierarchy the level of system intelligence will increase.

A designer of the crane may designate each hydraulic actuator and its hydraulic control valve as a power system, electronic control of the hydraulic valve as a control system and valve contamination control as an external system. If the control system is integrated physically with the power system and the operation of the power system is controlled with only rudimentary interaction with system I/O we refer to such an implementation as an embedded system. The functional structure of the crane will then consist of the main power system controlled by the control system that also interfaces with actuator subsystems (distributed control) and any additional external systems (e.g. power supply) [10].

From the above we may see that the power-control-external concept of the machine allows explicit identification and description of the control functions and in combination with hierarchical partitioning of the system will result in *small scale* design problems which can be individually solved.

## 4. ANALYSIS

System analysis task, that is the investigation of behaviour and properties of the system is based on the knowledge of inputs and the internal structure of the system, fig.8.

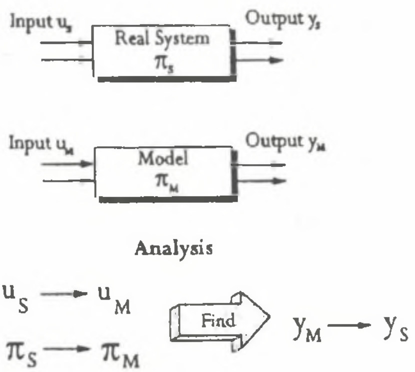



Fig.8.Analysis

Rys.8. Analizy

The analysis is performed in an iterative loop with synthesis and hardware implementation tasks. The results of analysis show system performance and provide guidance to any necessary design modifications. The success of analysis is based on the degree of knowledge of modelling techniques and mathematical methods of solution and most importantly on the availability of data.

All approaches to modelling require an insight into the physical laws and relations which govern the behaviour of various elements of the system, an appreciation of the interaction between system components and the knowledge of the structure of the system. Although in engineering practice various graphical and symbolic forms of models can be used to derive a set of system equations e.g. transfer function, vector-matrix model, block diagram, signal flow diagram, terminal graphs [11], the bondgraph technique is most suited to modelling of neuromechanic systems[12,13]. The neuromechanic systems are usually complex, non-linear, and combine mixed technologies. The bondgraph approach is based on the concept that the dynamic behaviour of a system which comprises of interconnected elements or components is dictated by the power being interchanged between the components or components and the environment. The power flow between elements is the product of two variables - a potential variable and flow variable. This implies a dual variable approach to modelling, a concept quite distinct from other approaches. Some advantages of the bondgraph approach are:

- topography of the model closely resembles system topography
- causality of the power flow is explicitly defined - probably the most important feature of this technique. The cause and effect variable are indicated on the graph
- uses only limited number of basic elements to model
- system equations can be written directly from inspection of the bondgraph
- the model can be easily modified - elements can be removed or added
- missing effects due to incorrect assumptions are easily identified
- complexity of the model can be easily increased/decreased
- technology independent - electrical, mechanical, hydraulic components are modelled using the same basic bondgraph elements
- system non-linearities are easily included
- very complex models can be developed (authors developed models which, when converted to block diagram, contained 2500 blocks!)
- the models are modular and can be *reused* in models of other systems
- effects of various dynamic elements are visible
- coupling of the models is easily performed
- the bondgraph models are easily converted into block diagram, or other form of models. This allows subsequent use of graphically interfaced simulation packages - ACSL, Vissim, Matlab
- resulting system equations can be easily checked for completeness.

The disadvantages of the technique are:

- unfamiliar terminology
- necessity to think in terms of *power flow* rather than in terms of *signal flow*.

The above disadvantages of bondgraph technique are easily overcome in only a few hours instruction. The necessity of thinking in terms of power flow is very natural to mechanical engineers as mechanical engineering is all about power transmission.

It must be noted that there is a direct equce between bondgraphs and other modelling techniques like block diagrams or signal flow diagrams. The choice is a matter of prior experience, convenience and characteristics listed above. The availability of graphic interfacing provided by, block diagram based, packages as ACSL, Matlab or Vissim make it attractive to develop system models using block diagrams. However, in the case of large, complex and mixed technology systems it is very advantageous to develop first the model using bondgraph technique, as it allows explicit determination of causalities and has a high level of self-checking of correctness of the model, and then convert this model to block diagrams to take advantage of these new packages.
The modelling task in itself is relatively small, no more than 10% of total modelling and simulation time is spent on developing the model. Most of the time is directed towards the task of getting correct parameter data and running numerical solvers.

The description of bondgraph modelling is given in a great number of publications and will not be repeated here. The methodology of bondgraph modelling of neuromechanic systems can be summarised as follows:

- decide what information about a system is to be determined
- prepare function diagram of the system, identifying primary and secondary functions as well as hierarchy of functions
- define the power, control and external blocks and indicate power transfer bonds
- extract the part of the system which is to be investigated and identify the points connecting it to other systems and the environment
- prepare a list of assumptions
- designate a set of input and output variables (the form of input need not be specified at this time)
- prepare a power flow diagram; i.e. replace each component by a *box* showing power ports
- for each *box* (i.e. component) identify the dynamic properties which should be included, i.e. C (capacitance), R (resistive) and I (inertial) one-port elements
- combine R,C and I elements using three-port elements (power junctions). Use "0" junction for parallel connections (summation of effort variables *velocities, currents, flows* and determine effort variable which is common) and "1" junctions for serial

connections (summation of effort variables *forces, pressures, torques, voltage* and determine flow variable which is common)

- introduce two-port elements (power transforming elements) where power is transformed; e.g. hydraulic cylinder transforms hydraulic to mechanical power
- define the independent power input variable (effort or flow source)
- assign integral causality to input variable and to each C and I bond
- using the rule that only one causal bar can be adjacent to "0" junctions (indicating the output flow from the junction) and only one bond without causal bar can be adjacent at the "1" junction (the output effort from the junction) assign causalities to the model. If causality conflict occurs inspect the model as it may indicate that some dynamic effects were ignored. Note that no two "1" or "0" junctions should be adjacent to each other
- assign causalities on R bonds. Usually causality can be in either form (i.e. either flow or effort) however when R element is non-linear care should be taken that correct causality is assigned
- write system equations for each junction and each one- and two-port element. These equations are in the form directly usable in standard modelling packages (for example ACSL). The equations should be algebraic rather than numerical (this will allow reusing the model with different input data)
- verify model completeness by checking that each (independent) variable on the left hand side of equation is used at least once on the right hand side in some other equation(s).
- identify any non-linearities and/or constraints and write their equations
- specify the control inputs and their form
- prepare the list of parameters and initial conditions
- solve it. There are a number of integration routines available and it is advantageous to experiment with different routines. The differences in accuracy, stability of solution and solution times will usually be evident.

## 5. CONCLUSION

The paper introduced a concept of neuromechanics to describe systems in which control functions are performed in an intelligent manner and which are interfaced with systems generating, converting and transmitting motions and forces. The concept of neuromechanics was developed to generalise a modern approach to design of power transmission systems and pave the way for introduction of as yet unknown control and mechanics technologies. Typical embodiment of neuromechanics are mechatronic systems in which electronics provides *smart* control of mechanical systems.

The paper discussed a functional approach to design neuromechanic systems which leads to clear delineation of power and external functional systems interfaced with a control system. This functional approach leads naturally to distributed architecture of neuromechanic systems and to development of embedded controls.

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