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SURVEY ON PHYSICALLY-BASED ANIMATION TECHNIQUES

Summary. Physically-based animation, thanks to the growing computing power of currently used computer hardware, has a chance to become a leading trend in the computer-aided animation of virtual characters. While synthesized motion may offer lower quality than recorded with motion-capture techniques, results are very promising.

Keywords: physical animation, motion capture, motion synthesis

PRZEGLĄD TECHNIK ANIMACJI OPARTYCH NA SYMULACJI FIZYCZNEJ

Streszczenie. Animacja oparta ns symulacji fizycznej, dzięki rosnącej mocy obliczeniowej obecnie używanego sprzętu komputerowego, ma szansę zostać wiodącym trendem w komputerowo wspomaganej animacji postaci wirtualnych. Mimo niewiele gorszej jakości ruchu syntetyzowanego w stosunku do technik motion-capture wyniki są bardzo obiecujące.

Słowa kluczowe: animacja fizyczna, przechwytywanie ruchu, synteza ruchu

1. Introduction

Currently, the majority of animation systems designed to function in interactive applications (games, virtual reality) are based on kinematic motion data acquired using the motion capture technique. This allows for high-fidelity motion, which can be easily played-back at interactive rates using contemporary computer hardware. The problem with this approach is that it offers only the prescribed motions which cannot change when the character's environment is changing (e.g. ground slope changes) or even actively acting upon it (e.g. by pushing or pulling). To hide this from the user/player, a number of tricks and techniques is applied, such as blending recorded motion sequences in a number of ways or combining them with ragdoll simulation and inverse kinematics.

To provide means for animating the character in perfect unison with its virtual surroundings researchers have focused on designing **controllers for dynamically simulated characters**, which is hard to accomplish and continuously under active research due to:

underactuation – there is no direct control over the global position and orientation of the character; they can be only indirectly controlled via external forces from the environment, ground reaction forces (GRF) mainly

- **high dimensionality** – characters have relatively many degrees of freedom (while it can be argued over, human body is often approximated by models having around 30-40 DOFs [29, 30])
- **lifelike motion** – the fact that the goal is providing an animation to be used in e.g. computer games, virtual reality, means that the resulting motion needs to look realistic, robot-like motions are unacceptable for virtual humans
- **interactive rates** – the control task needs to be realizable at interactive rates (30+ FPS)

2. Formulating control objectives

2.1. Joint-space tracking

The most obvious and presumably the easiest to realize method to control a virtual character is to represent the motion as a sequence of joint-space configurations (i.e. given by joint-space vectors providing a setting for each actuated joint) and using per joint PD/PID controllers to servo each joint separately/locally toward the desired configuration feeding back the difference between the desired and current configuration as the error. At the higher level, there is a finite state machine responsible for setting reference poses from the input sequence as well as other state-bound settings (e.g. per-joint PD gains, timing etc.). This technique was successfully applied to reproduce a wide range of motions (walking, running, jumping) in virtual, physics-enabled environments [1, 2]. Both hand-designed [1] and motion capture data [3, 2] has been used to provide reference poses with comparable success.

Using the motion capture allowed this simple control approach to achieve impressive, realistically looking motions, but further development of the joint-space servo approach has faced major limitations implicit in this technique, namely:

- in order to follow the motion faithfully, high gain tracking controllers need to be used; however, when a contact is made and the character is supposed to react to it in a physically-plausible way, high stiffness parameters make the simulation seem inflexible; therefore – each new motion or character requires either tedious manual tuning or time-consuming offline optimization to reach acceptable trade-offs [4]; [3] proposes to tackle this problem by explicitly reducing controller gains at joints affected by contact events that were not included in the reference motion; this technique is unintuitive and quite problematic to integrate with a systematic implementation

- it is not suitable for realizing whole body and manipulation tasks (e.g. lifting and dodging objects), which are extremely difficult to express directly in joint-space [5]
- it does not cope well with a demanding, irregular terrain and unexpected external interruptions (external forces) since it *blindly* drives the controlled character toward a reference pose without considering its surroundings.

Although the last of the aforementioned limitations has been addressed by employing explicit balance recovery strategies [2, 3] the *pure* joint-space controllers are slowly becoming classified as obsolete and abandoned by most researchers.

2.2. Task-space objectives

Because of the limitations resulting from the joint-space restraint, attention has been drawn to a so called **task space** control where the focus is on the task variables while the redundant degrees of freedom are kept as compliant as possible. This approach has a strong basis in behavioral studies [6]. In robotics, the theory of **operational space** control introduced by Khatib [7] tries to fulfill similar goals. At the coarsest level, the difference between the task space control and joint-space formulations is that we can express different goals of the control in terms of high-level tasks rather than as exact joint-space configurations.

A typical example of such a task is driving a certain point associated with humanoidal body in the desired direction (it usually requires determining the jacobian matrix to express its motion in terms of system degrees of freedom) [9, 13]. The control scheme will try to find driving torques minimizing the difference between the actual and *desired* accelerations of this point, which can be achieved by extremizing a properly constructed objective function. Thanks to the generality of this formulation reference motion tracking, most conveniently expressed in joint-space, can be easily treated as a special case task-space objective [5].

2.3. Self-sufficient motion controllers

Using motion capture as a source for motion reference allows for synthesizing high-fidelity, lifelike human motion and by using task-space control, the controller can adjust the motion in order to maintain/recover balance in the changing virtual environment. However, controllers built on top of pre-recorded trajectories are bound to generate only similar motions (which enforces an access to mocap studio and a time-consuming recording session whenever a custom motion is desired). To address this issue, a relatively new trend has emerged aiming at providing self-sufficient controllers generating motion without explicit referential data (*from scratch*) [9, 10]. As of now, however, although being robust and flexible, the controllers designed using this approach do not offer sufficient realism of the synthesized motion. What is more – they are not completely free from the burden of providing a reference pose since the motion tasks will very often not specify the torque for all actuated degrees of freedom so an additional full-rank damping task is needed to eliminate ambiguities [8, 9].

3. Combining different objectives

In previous sections it has been shown that a robust motion controller needs to realize several tasks at a time (tracking and keeping the character in balance, mainly). Joint moments generated to fulfill different objectives in general will be different, so a way is needed to combine/mix them. A technique easily applicable to the joint-space approach is to sum them [2, 3], but it is more of a simple *ad hoc* method than a technique justified in the realm of control or biology.

3.1. Null-space projection

Originally, the task space methods were based on a null-space projection [7, 5], which allowed for realizing the background operations (e.g. stabilization [7]) in the null space of the main task, i.e. not interfering with it. From a more general standpoint, null-space projection allows for multilevel priority system were lower priority goals are realized only to the extent that is not violating higher priority ones, which can be perceived as a definition of a **hierarchical control system**. However, the null-space methods do not cope well with unilateral constraints, which may not be a problem for a fixed manipulator system but becomes a serious obstacle when dealing with humanoid locomotion.

3.2. QP with weights

An approach alternative to null-space projection, offering similar possibilities and free from its limitations, is to combine all the tasks (either task- or joint-space) within a single quadratic program (QP) after having expressed them by a number of quadratic objective functions (Figure 1). Each objective, E_i, has its relative importance enforced by either using a corresponding objective weight, α_i [11, 12, 13]:

$$\min_x \sum_i \alpha_i E_i(x) \tag{1}$$

or applying prioritized optimization [9, 8], which means ordering all the objectives by task priority (highest to lowest) and consecutively trying to find the minimum, h_i, of each objective among the previously determined minimizers [8]; the sequence of consecutive optimizations can be formally expressed as:

$$\begin{aligned} & h_i = \min_x E_i(x) \\ & \textit{subject to} \quad E_k(x) = h_k, \forall k < i \end{aligned} \tag{2}$$

This approach frees the controller designer from the need to tune the weights and guarantees that different tasks will not interfere with each other, but is in general more costly in terms of performance and reportedly leads to less realistic motion when tracking the captured trajectory is among the tasks [11].

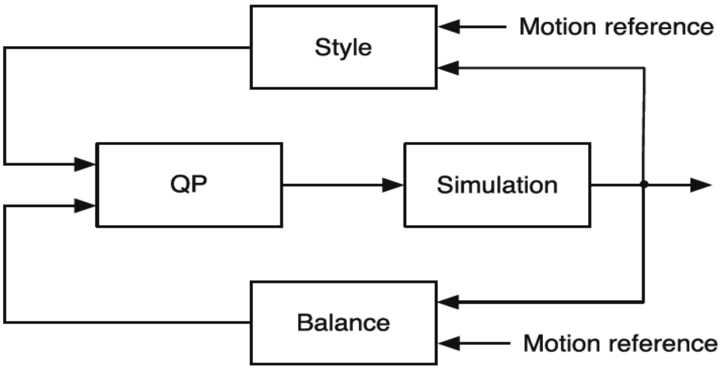

Fig. 1. An illustration of a typical character motion controller – this particular one has two objectives (tracking the reference motion for style and maintaining balance) fed to a QP block in order to determine the optimal control and use it to drive the simulated character [12]

Rys. 1. Schemat przykładowego kontrolera ruchu - w tym przypadku zdefiniowano dwa cele ruchu (śledzenie ruchu referencyjnego oraz zachowanie równowagi) podawane na wejście bloku optymalizacyjnego w celu estymacji (QP) optymalnego sygnału sterującego i wykorzystania go do sterowania postacią [12]

4. Human balance

4.1. Balance control as a basic control task

Generally speaking, balance control is about measuring/computing given stability indicators (*Section 4.2*) and keeping them within acceptable bounds (more detailed description provided in *Section 4.3*).

Obviously, problem of synthesizing human motion is complicated and computationally demanding. Without going into details, from purely robotic [28] or biomechanical [23] point of view, employing one or more balance strategies (static or dynamic) is considered as a fundamental control task, enabling creation of robust motion controllers. While above-mentioned reasoning is rather intuitive and produces reliable results for specific kinds of human motion like walking or running, care must be taken when synthesizing more sophisticated ones i.e. athletes performing various exercises [1].

4.2. Measures of human balance

Over the past decades a number of humanoid stability indicators have been proposed, most of them based on observation of how people maintain balance. The balance-related objectives of the motion controllers are mostly either directly or indirectly referring to this indicators/strategies. This section describes the most well known indicators and provides examples of how they can be related to certain virtual human controllers realizations.

A legged system is considered to be **statically** balanced as long as its centre of mass projection is kept within the support polygon formed by the feet [14]. If the motion is slow enough (i.e. system dynamics can be neglected) that static indicator can be used but these very assumptions allow only for a very limited and most unnatural motions. **Actively (or dynamically) balanced** system will temporarily leave the static equilibrium and this kind of strategy is characteristic to most of the animal motions [14]. However, as opposed to a well defined static stability measure, there is no single, commonly agreed definition of what dynamic stability is [13, 15]. Instead, there is a number of dynamic stability indicators briefly summarized below:

- **centre of pressure (CoP)**: the point on the ground where a single force equivalent to the field of normal pressure forces would have to act to produce zero moment [16]
- **zero (tipping) moment point (ZMP)**: the point on the ground where the tipping moment of forces acting on the system due to gravity and inertial forces is zero [16]
- **foot rotation indicator (FRI)**: the point on the sole where the net ground reaction force would have to act (in a single support phase of motion) to keep the foot stationary [17]
- **zero rate of angular momentum (ZRAM) point**: point on the ground where the net ground reaction force would have to act to produce zero rate of change of the system centroidal angular momentum [18]
- **centroidal moment pivot (CMP)**: the point where the CoP would need to be in order to obtain zero momentum change due to ground reaction forces [19]

Apart from defining numerous stability indicators, excessive behavioral experimentation has been conducted trying to determine what humans exactly do in order not to trip. This way the well known *ankle and hip strategies* have emerged [20, 21] and soon became a kind of biomechanical paradigm [22, 23]. The literal description of these strategies *is keeping CoM* *within boundaries of the support polygon by applying torques mainly to ankle* (ankle strategy) / *knee and hip joints* (hip strategy); in order to transform it into a control law, model must be chosen. Ankle strategy is often simplified as a problem of balancing the inverted pendulum in a sagittal plane, while hip strategy is approximated as double inverted one (Figure 2) [20].

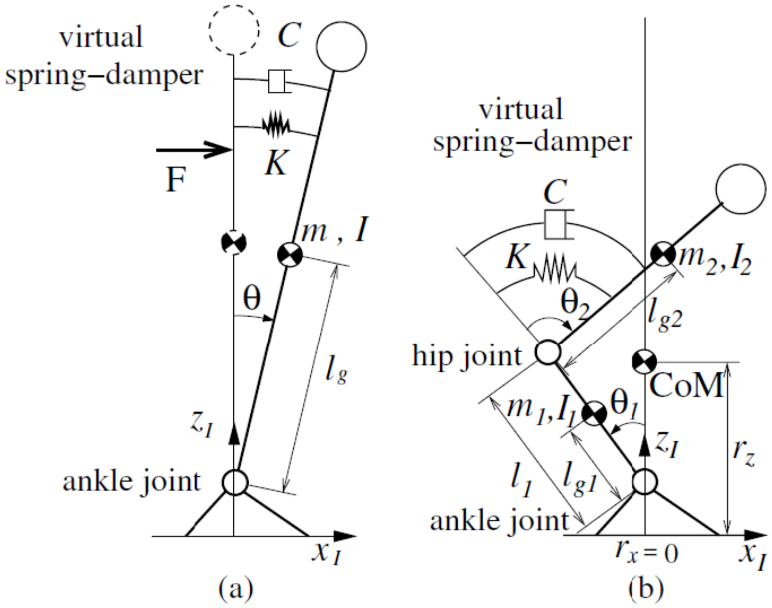

Fig. 2. Balance recovery strategy simplified to an inverted pendulum model: (a) single pendulum for *ankle* strategy; (b) double pendulum for *hip* strategy [20]

Rys. 2. Strategia odzyskiwania równowagi uproszczona do modelu odwróconego wahadła: (a) pojedyncze wahadło dla strategii *kostkowej*; (b) podwójne wahadło dla strategii *biodrowej* [20]

However, when balancing individual is exposed to stronger perturbations, above strategies turn out to be insufficient [24]. Nakada's experiments proven that employing arms rotation (ARS – arm rotation strategy) into balancing scheme, can significantly improve posture stability. Despite being natural and intuitive, there is no strict and clean definition of ARS, except rather trivial statement that *properly timed arms rotation can be used to minimize body angular momentum caused by falling* [24].

Another observation based on behavioral study and human motion analysis is that in a wide variety of motions (standing, walking and running in particular) humans tend to strongly regulate their angular momentum, since the total angular momentum about CoM remains almost constant while, by common sense, it should not be so, since the system is continuously acted upon by GRFs [25, 19].

4.3. Balance objectives

Computer graphics community has used (directly and indirectly) the above-described indicators and behavioral observations in various combinations when designing character motion controllers. Driving CoM projection towards the centre of the support polygon can be considered as a realization of the static balance condition and was applied in a number of motions. In [3] a virtual force acting on the CoM to encourage its projection to move in the desired direction was first determined and then expressed in joint-space by a set of per-body force-moment transformations equivalent to using CoM Jacobian transpose. In the QP approach, specific objective functions were included to achieve the same goal; [13] tried it by driving the rate of change of linear momentum toward a desired value, while [9] uses CoM acceleration directly.

The observation on the conservation of angular momentum has been reflected in further objectives realized by virtual motion controllers; [9] uses an objective function which seeks to regulate whole-body changes in angular momentum (zero in case of walking); [13] proposed a similar objective but enforced only when CoP is far from CMP (big distance between them is used as an instability indicator) – approach based on an assumption that humans tend to tightly regulate their total angular momentum only when performing rotationally unstable tasks.

The ankle and hip strategies have also been utilized in balance control; [26, 3] adjust ankle and hip angles offsets to try to drive the system CoM projection towards the centre of the support polygon while the nominal angles can be specified by other controllers/objectives. Some authors prefer to use rather heuristic balance strategies. [2] uses hip torque of the swing leg to indirectly increase the area of future support polygon whenever the humanoid is bound to lose balance. Similar idea is used by [27] but realized with far more precision by exactly planning the landing position of the swing leg, which can be done efficiently thanks to a simplified model of system dynamics – Inverted Pendulum Model (IPM). [12] has also used a simplified dynamical model for balance control – a three body structure (two legs and a torso) with stance leg attached to the ground by an unactuated spherical (3-DoF) joint (Figure 3); the balance recovery strategy is to try to return to a single reference pose for which the simplified system is in unstable equilibrium ("inverted pendulum configuration").

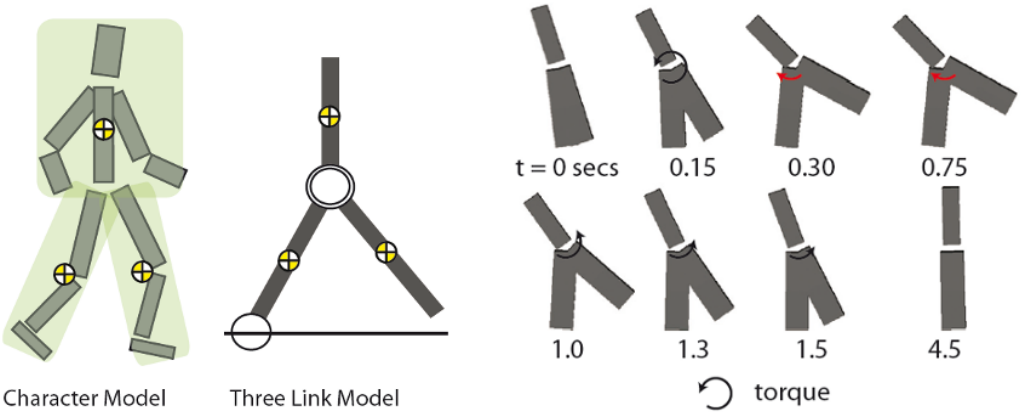

Fig. 3. Character dynamics simplified to a 3-link system attached to the ground by a spherical joint: (left hand side) full and simplified model; (right hand side) a sketch of a successful balance recovery (flywheel strategy) [12]

Rys. 3. Dynamika postaci uproszczona do modelu 3-segmentowego, przytwierdzonego do podłoża poprzez staw sferyczny: (lewy profil) pełny i uproszczony model; (prawy profil) zarys udanego powrotu do stanu równowagi [12]

5. Summary

As it can be seen, the once common core of research has ramified into several main branches, each offering certain advantages and disadvantages:

- joint-space control is simple, fairly fast to implement and can be easily applied at interactive rates on contemporary hardware, but it always needs a tedious parameter tuning or lengthy offline optimization and it becomes insufficient when designing a robust, flexible controller
- task-space control requires relatively high implementation effort and an online optimization procedure, which is hard to provide at interactive rates but the produced controllers are robust, flexible and capable of performing fairly complex manipulation tasks
- motion-capture based controllers offer lifelike motion of heavily limited flexibility; conversely, controllers designed to function without referential pose data yield flexible but unnatural motion
- there is no commonly used definition of **dynamic balance**, while there are many *dynamic balance indicators* (CoP, ZMP, FRI, ZRAM, CMP)
- on the other hand, **static balance** is well-defined (see *4.2*), but has very limited applications (like synthesizing standing or walking individual)
- new balance strategies are being researched (like ARS, employing arm movement), basing on behavioral studies

Depending on a particular application, a properly dosed mixture of these approaches seems most reasonable. At the same time, it is safe to say that the future animation controllers will be standalone (no mocap) and high-level goals based and this is what research should be mainly focused on.

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Omówienie

Poza zastosowaniami *stricte* medycznymi, komputerowo wspomagana animacja wirtual.-nej sylwetki ludzkiej, jest wykorzystywana głównie w aplikacjach interaktywnych, w szczególności – grach komputerowych. Do niedawna synteza ruchu ludzkiego była trudna do osiągnięcia na poziomie interaktywnym (ok. 30 klatek/s), co tłumaczy popularność rozwiązań bazujących na przechwytywaniu ruchu (mocap). Pomimo trudnego do osiągnięcia (przez inne rozwiązania) naturalizmu mocap'u, podejście to jest bardzo nieelastyczne i pozwala tylko na ograniczoną interakcję animowanej postaci z otoczeniem. Obecnie intensywnie rozwijana technika animacji, gdzie część symulacyjna bazuje na prawach fizyki i dynamice brył sztywnych (zwana dalej *animacją fizyczną*), mimo swoich ograniczeń (wysoka wymiarowość problemu, problemy z nierównym terenem, reakcja na siły zewnętrzne), pozwala na osiągnięcie obiecujących wyników, a syntetyzowany ruch posiada jakość zbliżoną do zarejestrowanego ruchu ludzkiego (mocap).

W typowym podejściu animacja fizyczna może być rozpatrywana jako problem sterowania. Niestety, złożoność postaci ludzkiej niemal całkowicie uniemożliwia zastosowanie wyłącznie prostych kontrolerów PID/PD – typowe rozwiązanie opiera się na sterowaniu hierarchiczne, gdzie cele są definiowane w przestrzeni stanów bądź w przestrzeni zadań (z opcjonalnym śledzeniem mocap'u).

Istnieją różne strategie łączenia celów sterowania, kanoniczne podejście to projekcja do tzw. przestrzeni zerowej – alternatywnie można problem sprowadzić do zagadnienia programowania kwadratowego.

Intuicyjnie, podstawowym zadaniem sterowania jest utrzymanie równowagi sterowanej postaci. O ile równowaga *statyczna* jest zdefiniowana precyzyjne, trudno odnaleźć jednoznaczną i uznawaną definicję równowagi *dynamicznej*. Jednakowoż istnieje cały szereg wskaźników równowagi dynamicznej, takich jak CoP, ZMP, FRI, ZRAM lub CMP. Dla ułatwienia, często cały układ dynamicznie balansującego humonaida sprowadza się do problemu odwróconego wahadła. Dodatkowo są poszukiwane nowe strategie utrzymywania równowagi, bazujące na studiach behawioralnych, np. ARS, wykorzystujące ruch wypadowy ramion.

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