Dynamics-Based Motion Synthesis by Simple Learning Control

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Abstract
Point-to-point motion of a humanoid agent (or any mobile creature) is considered as a composition of basic movements related to the degrees of freedom. With time/energy performance criteria, such movements can be synthesized by using simple control functions. Natural looking animation can be achieved employing even very simplified dynamics models. Their parameters can be estimated or identified using motion capture data. In case no appropriate dynamic model is available, we propose an efficient procedure of direct motion editing. The captured motion can be re-used in order to animate the original or other characters in a variety of similar motion tasks. The proposed approach for motion synthesis is applied in the case of a six-link biped. Two examples are considered: one for editing captured walking motion and the other of direct motion synthesis for climbing stairs. The proposed methodology is very appropriate for interactive character animation.

I.3.7: Animation, I.4.8: Motion, I.2.8: Problem Solving, Control Methods, and Search

1. Introduction

When looking at the area of figure animation there is much work being done, but it is also evident that there is much to be done. It is due to the continuously increasing demands for more realistic performance of the animated figures as well as for lower cost of the animation work. Motion simulation of articulated structures such as humans or animals has been especially challenging due to the great number of joints and muscles resulting in complex multibody and muscle/tendon dynamics. There have been developed two main concepts for motion synthesis with physics-based considerations: to employ dynamic models and to utilize motion capture data.

There are mainly two dynamics-based approaches to generate animated motion: to treat the motion animation tasks as trajectory optimization problems[25,5,14] and the other one is to devise control algorithms that can synthesize desired trajectories or point-to-point movements using direct dynamics[20,18,17,15,27,12,24]. The search for controllers that enable physics-based models to produce desired animations usually entails formidable computational cost[8].

Generally speaking, dynamics parameters can be estimated from given mass/geometric data or directly identified using motion capture data. But full dynamics models that accurately describe the complex motion of articulated structures are difficult or impossible to derive and identify. On the other hand, motion simulation, based on mathematical models, should not be computationally cumbersome and time consuming according to the animator's demands. The animator should have access to a simple, yet flexible set of movement commands that can generate a variety of instances of motion tasks[3]. A major concern in constructing a goal-directed animation system is the degree to which a task should be parameterized in order to produce variations in locomotion.

Even if a motion simulation procedure involves full dynamics models, there is no guarantee that the animation will be natural looking. The dynamic performance of a mobile system depends on how the control functions drive the system after all. This motivates the approach of many researchers using neural nets and learning techniques for motion simulation. The challenge of *learning* motor-control functions must thus be addressed if we plan to use physics-based simulations for animation of controlled agents[17,7,15,8, 24].

A common feature of most physics-based simulation techniques is that the number of optimization parameters, especially in animation of humans/animals is very large, thus increasing the possibility to obtain local optimal solutions that do not give natural looking animation. Moreover, the time of optimization in most cases is so long that it makes such procedures inappropriate for animation use. Generally speaking, the question of what to parameterize and how to optimally choose decision parameters is very important in any design optimization procedure. Our control strategy in motion simulation is to define and use as optimization variables only those control parameters that considerably influence the performance indices of the controlled system[10,13,12]. Standing-up motion of human is considered in[11,12] and natural looking animation has been achieved employing properly simplified dynamics models.

The easiest way to animate human motion is to record the motion data of a real human being and to map it into computer characters. Nowadays, it is not difficult and expensive to obtain realistic motion data through kinematics/kinetics measurements. The data can be gathered from film or video (rotoscoping) or from sensors pasted on live actors (motion capture). Several techniques, based on motion capture[4,26,15,2,21] have been recently developed for animating humans in motion tasks similar to the original one. A common concept in these motion capture manipulating techniques is to use kinematics relations in generating new animations. This is reasonable when the parameters representing the new motion task do not differ so much from those of the captured motion and the motion under consideration is not so dynamic one. Otherwise, the dynamical realism in the original, captured motion is very likely to be lost. In general, any kinematics-based technique for motion simulation needs the animator’s assessment of the synthesized motion, because there are no physically defined criteria for motion selection.

To preserve the naturalness of the original motion when considerable “retargeting” is needed, we have to find and apply an appropriate dynamics-based approach. Our study on human animation with reusing motion capture is based on the concepts and the direct-search approach developed in our previous work. In case no appropriate dynamic model is available, we propose an efficient procedure of direct motion editing. In this way, the captured motion can be re-used in order to animate the original or other characters in a variety of similar motion tasks.

The proposed approach for motion synthesis is applied in the case of a six-link biped. Two examples are considered: one for editing captured walking motion and the other of direct motion synthesis for climbing stairs. The control parameters can be quickly calculated (learned) which makes the proposed methodology very appropriate for interactive character animation.

2. Dynamic Modeling and Problem Statement

Dynamic systems representing humans/animals are very complex and difficult to model, identify, and control due to inertia couplings, gravitation forces, visco-elastic effects, and highly nonlinear actuator characteristics. In general, for a simulation technique to be efficient, some optimal tradeoffs between efforts/time spent on full dynamic modeling, accurate system identification, and motion optimization have to be found. Applying the Lagrange formalism, the dynamic performance of any single- or multi-body system can be, in general, described by the following system of differential equations

$$\ddot{q} = M^{-1}(q)(BF - C(q,\dot{q}) + g(q)) \qquad (1)$$

where q is the vector of l generalized coordinates (e.g., links' rotation angles or joint angles), $M(q)$ is the inertia matrix, $C(q,\dot{q})$ is the vector of velocity forces, $g(q)$ stands for friction and gravitation forces, F is the vector of control forces; matrix B represents the control force distribution, and $A = M^{-1}(q)B$ is the control transfer matrix (TM);

As the objective of this paper is to present the main features of our control design method, we will not here address the actuator (muscle) or tendon dynamics. That how detailed actuator dynamics models are to be employed depends on the objectives of human motion simulation: whether it is to be used in biomechanical engineering, human animation, virtual reality, or robotics. For example, an ultimate goal in the human motion simulation, especially for the purposes of physiology and virtual reality, is to find what are the neural excitation functions for the muscles activation or even the commands from the central nervous system for a motion task to be performed.

It is very important to know what are the independent state variables best describing the dynamic performance in a specific motion task. For example, during human locomotion, the set of the generalized coordinates has to be changed four times when performing a step[13] to describe the biped motion during each phase: double-support, taking-off, single-support, and landing. In this case, the dynamics of human locomotion changes its structure at least four times, and, accordingly, the control system should have different structures.

For simulation and animation of point-to-point motion tasks, we consider that satisfying the required final conditions is a problem of primary importance. Mathematically speaking, a point-to-point motion task is to transfer the dynamic system (1) from a given initial state $\{q^0, v^0\}$ to a required final state $\{q^f, v^f\}$. We have to solve the two-point boundary-value problem (TPBVP)

$$\begin{array}{l}\{q(t^0)=q^0,\dot{q}(t^0)=v^0\}\mapsto \\ \{q(t^f)=q^f,\dot{q}(t^f)=v^f\}\end{array}, \quad (2)$$

in such a way that a performance criterion $J(q,\dot{q},F)$ is optimized and a set of control and state constraints are satisfied. The control constraints are due to the limited power resources, strength bounds and comfort demands, or due to a task for force interaction with the environment. The state constraints can be geometrical or kinematical (e.g., when a trajectory to be followed). If we have to satisfy space or force constraints at each instant we have to design and apply closed-loop, trajectory tracking controllers[12]. If there are no such constraints and the required point-to-point movement can be performed in a free manner, then we consider open-loop control synthesis and have to find the best among all the feasible solutions of the TPBVP.

3. Dynamics Simplifications for Efficient Animation

We have to choose properly simplified dynamic models with easily identifiable parameters which can be used for efficient control design. The degree, to which a simulated system should be accurately modeled, identified, and control depends on the purposes of simulation: animation, virtual reality, robot design, or biomechanical engineering. In any of these areas, the controlled dynamics are very complex multi-input multi-output systems and researchers prefer to work with models that are as much decoupled as possible.

For the purposes of animation and virtual reality, we also have to consider proper simplification of the dynamics models for our control synthesis to be more interactive. In view of the considerations in the previous sections, we find that, for the purpose of physics-based animation, the following reduced dynamics models may be appropriate

$$m_i\ddot{q}_i = u_i - f_i(q,\dot{q}), \quad (3)$$

where q_i is the *i*-th controlled output (generalized coordinate), u_i is the corresponding overall control force representing all the muscle forces driving q_i, $f_i(q,\dot{q})$ stands for the other (not control) forces that may effectively influence the dynamic performance (e.g., gravity or drag forces),

The structure of (3) is similar to that considered in[7] and can be viewed as a generalization of the stimulus-response model used in[17]. The control-decoupled dynamic equations (3) may be appropriate to both identify their parameters first, and then, design controller for any degree of freedom. Moreover, when employing such models, there is possibility for practical dynamic/control scaled animation:

- with greater/smaller values for the inertia coefficients m_i we can consider motion tasks for more/less massive subjects;
- with the term of position/velocity dependent forces $f_i(q,\dot{q})$, we can consider motion in the presence, e.g., of gravity or drag forces;
- to simulate/animate the motion of more powerful, e.g., humans, we have to consider larger magnitudes for the control forces u_i.

External forces in case of human motion: If we know the geometrical and mass parameters of the human body parts and consider the case when $f_i(q,\dot{q})$ represent only the gravitation forces then these dynamic terms can easily be calculated. For example, such may be the case of walking on hard terrain at normal speed when the human motion is not so dynamic for the velocity (centrifugal, Coriolis, friction) forces to attain considerable values. In other cases, we have to properly parameterize and identify the external forces.

The number of parameters describing the external forces $f_i(q,\dot{q})$ as well as the control forces u_i as functions of time or state will depend on how dynamic and how large is the corresponding point-to-point movement.

4. Learning Control for Dynamics-Based Character Animation

In voluntary movements, where no space or force constraints are imposed, it is natural to assume that such point-to-point movements are controlled in an open-loop manner. Our purpose is to devise algorithms that can give human (or animal) models the ability to learn how to move accurately. We have to be able to find all the controls driving the corresponding parts of the body to the specified positions. To do that, we have to consider first the primitive point-to-point movements where our simulated creatures will acquire basic motor skills. We consider a motion task (e.g., performing a stride or a reach motion) as a composition of several sub-movements. For example, an arm reach motion can be divided into two segments: motion from the rest to the target, and return to rest. In each of such “monotonic”, primitive movements, the structure of the dynamics is not changed and the velocities of the body parts do not change their signs, too.

A direct-dynamics method, based on a generate-and-test strategy that optimizes the control objective functional through repeated forward dynamics simulation and motion evaluation, is proposed. We use only those control parameters, namely magnitudes, switch times, and slopes of switching that mostly affect the reached position and the time/energy dynamic performance criterion. This minimum set of parameters describing such test control functions are the control parameters to be learned. It is interesting to note that our control learning parameters are similar to those used by the human in voluntary movements[9,11]. The main steps of our control learning procedure are as follows.

1. *Choose a set of appropriate test control functions*: When a human movement is performed, it is difficult or impossible in general to say what the performance criterion is. With usual voluntary movements (when there is no specific emotion), it is reasonable time and energy cost to be taken as performance indices[1]. In such cases, the optimal control laws can be well approximated by simple spline functions of "bang-bang", "bang-pause-bang", or "bang-slope-bang" type[10]. Parameters $p_i, i = 1,...,n, n > l$, describing the test control functions like magnitudes, switch times, slopes of switching, or pause lengths, mostly influence the final position to be reached as well as the time/energy performance criterion.
2. *Define the most relevant input-output pairs*: In order to satisfy the required final conditions (2), we have to assign two parameters for each generalized coordinate. For simplicity in explaining input-output pairing, assume that the end-point velocities v^0, v^f are zero, i.e., the human is doing a rest-to-rest movement. We define l controlled outputs to be the reached positions $y_i = y_i(p) = q_i(t_i^f)$, where $\dot{q}_i(t_i^f) = 0$. Then for each controlled output y_i we have to assign a control input p_i which mostly influences it. With specified control force magnitudes, such control inputs are the corresponding switch times. With such input-output pairing, the necessary independent parameter controllability and existence of feasible solutions can be guaranteed[10].
3. *Solve shooting equations and perform control parameter optimization.* With the above input-output pairing, the given TPBVP is transformed into a vector shooting equation $p \Rightarrow q^f$. We can solve this equation by the bisection algorithm which is robustly convergent and uses minimum function evaluations. Finding feasible solutions is the first level in our control synthesis procedure. As regards the performance optimization, we need to find first the time-optimal solution, and then to consider the energy minimization problem with pre-specified movement execution time. Then, using pauses lengths or slopes of switching as optimization parameters yields satisfactory minimization of the energy cost. With these parameters, we also achieve synchronization in motion completing for all the body parts.

With our learning scheme, in contrast to most schemes using neural nets, there is no problem of parameter redundancy. Moreover, unlike the space-time constraint approach which discretizes both the state and control variables, our approach involves only control parameter optimization. Following the proposed approach, one has the chance to find satisfactory suboptimal solutions of the respective TPBVPs with minimum number of decision parameters. As the method proposed in this section can be considered also as a procedural, simulation-based one, and can offer representations independent of the character, it may be used to generate new motions for new characters.

Our concepts for control design are not in conflict with the so-called concepts of *zero-crossing* and *co-occurring spatial proximities of end-effectors with neighboring objects,* considered in[2]. The latter concept is also a basic one in the well-known space-time approach[25,5,6]. Indeed, driving a system from rest to rest implies there must be points where the system's accelerations change their signs.

Knowing how to control certain classes of dynamic motions, we will be able to provide the animator with a minimum set of movement commands and parameters which completely control the animated figures. Taken together, such elements will allow us to compose movements of general nature[19].

5. Re-Using Motion Capture Data

In the previous section, we proposed a control learning method which needs a dynamic model and a performance criterion to simulate motion tasks. For a specific character, it is often difficult to find appropriate model and also motion synthesis criteria, except for movements where time, energy, or smoothness can be a relevant performance criterion. In what follows, we consider the possibility to utilize the available kinematics data for a movement of a character and generate similar new motions. Taking full advantage in using motion capture data, we may not need dynamic models or performance criteria.

Motion capture is the process of recording motion data in real time from live actors and mapping it into computer characters. We consider the possibility to apply such data from the primary agent to another figure (having, in general, different segment lengths) with identical structure (connectivity of links, number and type of joints). The so-called "retargeting motions" should be synthesized under the condition to preserve the realism and other desirable qualities of the original motion[6].

We find that the control learning approach, as above proposed, can be very practical in re-using motion capture data for dynamics-based animation of a variety of similar motion tasks. To explain first what we mean by "similar", let us consider biped locomotion. Suppose we have the motion capture data when the primary agent performs strides with specified length and rate. With new terrain conditions close to the original ones, we believe that, if the required step length and rate do not differ so much from those with the motion capture, similar animation can be obtained using even simplified dynamic models (3). In other words, this will enable us to preserve the naturalness in animation of the original motion for a set of similar motion tasks (in a "neighborhood" of the captured movement).

Besides the terrain conditions, there is no change also in all the other parameters of the environment (e.g., wind, obstacles) that can remarkably influence the controlled dynamic performance during locomotion. In general, we assume that the external forces in (3) are either known or they do not substantially change for the set of motion tasks under consideration; Similar movements means also similar control functions conforming to one and the same set of performance criteria. Although the performance indices may not be known analytically, it is reasonably to assume that they depend continuously on the control functions as well as their first derivatives, if we wish to consider movements without jerks. In similar movements, the values of those criteria should be close and this can be provided if the norms of the corresponding control function and its derivative in time are bounded. Such a control performance requirement is in accordance with most of the previous ones[25,23,5,16]. That will make possible preserving the main dynamic performance features of the original motion.

With all the above assumptions, we will show how easily and quickly one can synthesize point-to-point motions similar to the captured motion of the primary character. For the sake of simpler explanation, we will consider the case when the initial and final times are the same for the motion capture test and for the similar movements. Otherwise, we have to re-sample the original motion to fit the new final time.

First, we have to make the dynamics model (3) a non-dimensional one, in order to reduce the dependence of the simulation results on the geometrical and mass parameters. When the motion is without translational degrees of freedom, then the dynamics can be described by only angles that are independent of the scaling of the limbs. Denote by bar and wave signs the control, initial and final states in the dynamics models of the motion capture and a similar motion task, respectively. As in[6], we have to augment the dynamics motion data by specifying constraints that are essential to the point-to-point motion tasks: the initial and final conditions for the state variables.

$$\ddot{q} = \bar{u} - f(q,\dot{q}) \qquad (4)$$
$$\{q(t^0)=\bar{q}^0,\ \dot{q}(t^0)=\bar{v}^0\} \mapsto \{q(t^f)=\bar{q}^f,\ \dot{q}(t^f)=\bar{v}^f\}$$

$$\ddot{q} = \tilde{u} - f(q,\dot{q}) \qquad (5)$$
$$\{q(t^0)=\tilde{q}^0,\ \dot{q}(t^0)=\tilde{v}^0\} \mapsto \{q(t^f)=\tilde{q}^f,\ \dot{q}(t^f)=\tilde{v}^f\}$$

To utilize motion capture data for the animation of another similar motion, that is to find the "motion displacement", we have to be able to solve the following simple TPBVP

$$\ddot{q} = \tilde{u} - \bar{u} \qquad (6)$$
$$\{q(t^0) = \tilde{q}^0 - \bar{q}^0,\ \dot{q}(t^0) = \tilde{v}^0 - \bar{v}^0\} \mapsto$$
$$\{q(t^f) = \tilde{q}^f - \bar{q}^f,\ \dot{q}(t^f) = \tilde{v}^f - \bar{v}^f\}$$

As we need smooth retargeting, the control function $\Delta u = \tilde{u} - \bar{u}$ for the motion editing has to be bounded along with its time-derivative. Therefore, we have to seek a solution of (6) using test control functions of the shape presented in Fig. 1.

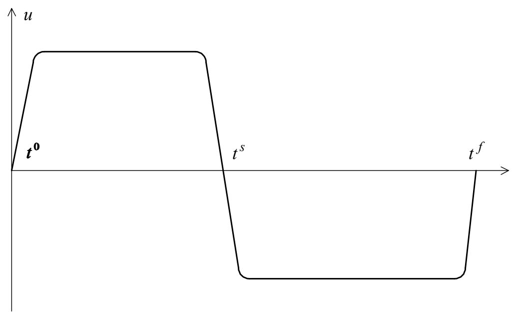

Fig.1: Test control function for motion editing

Motion generation from the captured data can be viewed as a dynamic system whose input is the captured motion data, and the output is the motion parameters to activate the imitator. Thus solving (6), we can find the control function change with minimum norm which is necessary to adapt (4) to (5).

Although most motion capture systems are equipped with some filters, they cannot guarantee that the filtered motion is the exact replica of the actual motion[22]. From the above considerations, it is evident that the proposed method can also be very useful in post-processing the motion capture data itself.

6. Case-Studies on Motion Synthesis of a Planar Six-Link Biped

6.1. General considerations

In the case of walking or stairs climbing, there is always at least one foot on the ground and the position and configuration of the animated figure can be determined by a footplant and the link rotation angles.

First, we decompose the locomotion process into the following basic phases: double-support (DS), taking-off (TO), single-support (SS), and landing (L). The reasons to do such decomposition are not only due to the different kinematics - each of these phases is characterized by its specific dynamics and number of degrees of freedom. When the structure of a dynamic system is changed, correspondingly, the structure of the control system has to be changed. For our articulated figure (a six-link biped), it means that the number of fixed, free, and activated joints changes. Generally speaking, we have to consider control design problems with different dynamics models in different phases.

In the normal or dynamic human walking, the time duration of DS-phase is relatively very small and the state variables do not change their values remarkably in this phase. For walking animation purposes, it is not necessary to perform any control design considerations for DS-phase. Instead, during the other three phases, the state variables may change significantly their values mainly due to leaving/striking the ground and gravitation forces, which effects may increase according to the dynamic performance requirements.

Except for the SS-phase, the other two phases, TO and L, can be featured by rapid, but monotony change in the link (especially the foot) rotation angles. During SS-phase, the link velocities usually change their sign twice. The thigh and the shank change the direction of their rotation in order for the corresponding leg to shorten its length and clear the ground. Although the whole SS-motion can be described using only one dynamic model, we have to further decompose that motion according to the time intervals of monotony. Besides the usual change in the sign of the shank rotation velocity of the transferred leg (in a short time interval after its TO-phase, the velocity of the thigh may also change its sign just before the next L-phase. Observing possible irregularities in the terrain, the latter change is needed for the human to walk with the necessary stability. This manner in driving the swing leg to perform a step is found also to be optimal with respect to the time/energy optimization[13] during SS-phase.

With the proposed decomposition of the locomotion process into five successive point-to-point movements, we can assume that the external and control forces (considered as functions of the corresponding angle), in each of these point-to-point movements, do not have to change their norm considerably if we want to adapt an already synthesized (captured) motion from one animated human to another.

6.2. Example of motion editing

For the purposes of motion editing, it is appropriate to use the non-dimensional dynamics model (6). In this way, the possibility of the qualities of the control design to depend on the links lengths (and the step length) is minimized.

A captured motion of a human walking on even terrain is represented by Fig 2a. It can be seen in this picture that the swinging leg does not clear the ground. Our task is to edit this motion in such a way that all such unrealistic visible effects are removed and the inherent features of the dynamic performance are preserved.

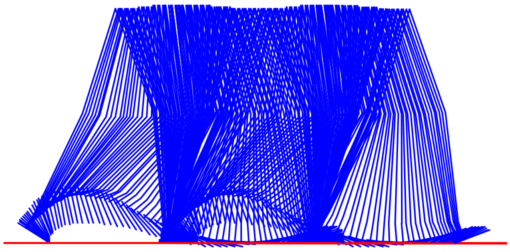

Fig. 2a: *Before editing*

Applying the method described in the previous section, we edit the basic movements in TO-, SS-, and L-phases with changing the boundary conditions in (6) until a realistic animation is obtained, Fig. 2b.

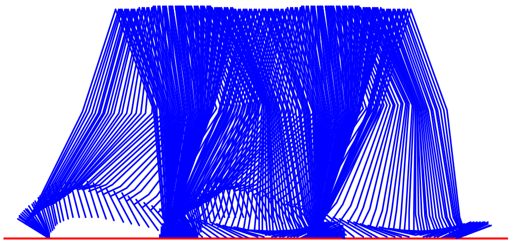

Fig. 2b: *After editing*

In order to re-use dynamics model (6) for control optimization in performing strides with different rate, we can consider the control and the external forces as functions of q, only. That will be possible if the locomotion is considered as a composition of monotonous point-to-point movements, where the velocity of any generalized coordinate does not change its sign.

We believe that our dynamics-based method of re-using motion capture data can be efficiently applied even for radical reshaping the original motion, and the main dynamic performance criteria will be still satisfied.

6.3. Example of direct motion synthesis

The task is to generate a dynamics-based animation of a biped climbing some stairs. Its dynamics is represented by Eq. (3) with some specified values of dynamic parameters. If the biped is a concrete human, such values can be estimated from the available data of the corresponding human dynamics. If the biped is not a concrete human, then the animator has the freedom to choose some appropriate values of the dynamic parameters in (3).

In order to obtain a realistic animation of the climbing motion, we have to choose also appropriate values for the final states in all the TPBVPs (2) that we have to solve. They have to conform to the geometry and the driving capabilities of the biped. All the TPBVPs in our computer simulation were solved applying the approach proposed in Section. 4 by using time/energy efficient control functions. The synthesized motion of the biped climbing pre-specified stairs is depicted in Fig. 3.

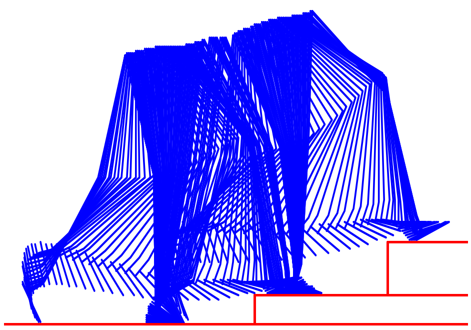

Fig. 3: *Motion synthesis in stairs climbing*

7. Discussion and Conclusion

A major concern in constructing a goal-directed animation system is the degree to which a task should be parameterized in order to produce variations in locomotion. The animator should have access to a simple, yet flexible set of movement commands that can generate a variety of instances of motion tasks. The user should be able to specify locomotion attributes such as the amount of foot clearance during swing, the maximum rotation of the pelvis, etc.

Our concepts for dynamic modeling and control design are in accordance with the above demands. The main advantages of the proposed approach for control optimization are the following

- smooth retargetting with minimum number of control parameters;
- there is no need of applying inverse kinematics techniques;
- simple dynamic models can be employed to represent 3-D human motion during each phase;
- quick and easy method of reusing motion capture data when similar motions are to be synthesized;
- feasibility and convergence in the control synthesis can be guaranteed;
- possibility to develop a real-time control-by-learning procedure for animation and VR purposes.

The proposed approach appears rather natural also for blending together existing motions with dynamics-based smooth transition between them. In this way, the motion data will seamlessly transit the boundaries from one motion clip to another. As the use of motion capture is very popular and the libraries of realistically animated motion become richer and richer, providing methods of dynamics-based motion editing can be of great value to animators.

In general, 3D-model-based control of dynamically simulated humanoid agents, is a highly complicated problem due to the high dimensionality of the model and design parameter space. Our ultimate *goal* is to build an entire dynamics-based animation system, where different classes of motions (locomotion, grasping, standing up, turning, etc., can be synthesized by the animator using a few motion and control parameters.

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