Simulation of human motion using a Sensory-Motor approach

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Abstract: - A Sensory-Motor approach is presented for controlling and synthesizing human skilled gestures which keep the main invariants of human gestures. In particular we propose a control model of articulated kinematic chains according to the Synergetic principles which state that movement patterns are not explicitely programmed but are rather emergent properties of a dynamical system constrained by physical laws in space and time. The model automatically translates a high level command specification into a complete movement trajectory. The understanding of mechanisms underlying the Sensory-Motor behavior is highlighted in this model by control theories in Automatics and Psychomotricity: a feedback loop uses the sensorial information of the movement to calculate the dynamical variables updating the current state of the system. These control principles are linked to higher-level control mechanisms and applied to the simulation of voluntary upper-limb movements, and to locomotion. A validation of the synthesized movements is presented. *IMACS/IEEE CSCC'99 Proceedings*, Pages:5651-5656

Key-Words: - motion control, control of limb movements, control of locomotion, biokinematics, computer simulation

1 Introduction

The simulation of biological articulated systems increases our understanding of natural motion and can be applied in different computer fields such as robotics or computer animation.

Motion control, though very widely studied, raises two main problems. The first one is relative to the excess of degrees-of-freedom, which traduces the difficulty to infer the effectors motion from perceptive feedback. The second one is based on the dependency of the movements according to the context, which implies the adaptation of the action to reactions of the environment.

This paper proposes a theory and implementation that suggest how movement and coordination might be developed by human or artificial systems. The theory relies on the reactivity and the adaptation of the system to the environment, and this is achieved at two levels. The first level is composed of a biologically-inspired model which provides a functional understanding of the sensory-motor system involved in the production of movements. The second level of reactivity is characterized by adaptive motor programs, which have the ability to modify the strategy of control relatively to the reactions of the environment. The motor programs differ, if the produced movements are intentional movements or automated movements. The sensory-motor system relies on the continuous confrontation between sensory (visual feedback) and motor signals to control the multi-effector system. This is an inverse problem of finding the appropriate control parameters of a nonlinear multi-dimensional system to achieve a desired end-point goal. We know that there are an infinite number of solutions to this problem, but we think that some solutions are better than others, in terms of the smoothness of the articulatory transition between the actions. Our solution uses sensory and motor coordinates to adaptively update the state parameters of the multi-joint system. Moreover, the introduction in the optimization process of elements whose structure and parameters have a pertinent biological meaning [1] allows the synthesis of movements which keep the main invariants of human gestures. In this sense, our approach contrasts with classical adaptive control methods in a major way: it is more devoted to explaining physiological aspects of human motor control than to optimizing processes for robotics. In particular, the control mechanism does not maintain the dynamic response of a geometric or physical device in accordance with some pre-specified trajectory. Two studies are presented in this paper, which both use the low-level sensory-motor system, and propose two ways of driving it. The first study is dedicated to the generation of intentional gestures and is applied to the synthesis of French Sign Language. The second study, in progress, focuses towards the specification of a high-level reactive model to animate synthetic human figures.

2 Basis of the approach

We adopt as a working basis for the Sensory-Motor system the Synergetic view: invariant properties of movements emerge from self-organized principles rather than from an explicitly pre-computed trajectory. The basis of such a system is detailed in [2] and resumed in the following section.

2.1 The Sensory-Motor Model

The state vector $\vec{q}$ characterize the state coordinates of the motor system at any time. The Observable signals, $\vec{a}$, measured in the cartesian space, are the movement output used as feedback signals to control the motion execution in real-time. The Task space is the vector space in which environmental specification of tasks are given to the operator: This task vector, also called the target vector, is used together with the observable data to modify the state of the articulators. It may represent a perceptive trace extracted from previous experiments.

The state of the articulatory system $\vec{q}$ is computed on the basis of the error between the current location $\vec{a}$ and the target location $\vec{a}_t$ expressed in the cartesian space, as stated by the following differential equation:

$$\begin{aligned}\frac{\partial \vec{q}}{\partial t} &= -g(E(\vec{a},\vec{a}_t,t)).grad(E(\vec{a},\vec{a}_t,t)) \\ &= -g(E(\vec{a},\vec{a}_t,t)).(\frac{\partial M}{\partial \vec{q}}).(M(\vec{q})-\vec{a}_t)\end{aligned} \qquad (2.1)$$

where M is the transformation which links the state observation vector $\vec{a}$ to the state vector $\vec{q}$: $\vec{a}$ = M($\vec{q}$) ; $(\frac{\delta M}{\delta \vec{q}})$ is the Jacobian matrix of the operator *M*, *g* is a gain function and *grad* the gradient operator.

Using a direct feedback with a constant gain function does not allow to damp large angular variations calculated through the error *E*. It is possible in fact that transitions in the adaptive loop trigger instabilities in some particular configurations. In order to ensure the stability of the system and to generate damped behaviours, a nonlinear function and a second order filter have been introduced. The nonlinear function has a sigmoïd shape: the gain of this function increases significantly when the error between the observable position and the reference target position is goes towards zero. Stability and asymptotic properties of such a model have already been studied in [2].

Such a model can be applied to the control of an artificial kinematic chain. An elementary task consists then in assigning a desired position to the chain end-point. The state vector $\vec{q}$ represents the angular observable vector, $\vec{a}$ is the location of the end-point of the articulated system, and the task vector $\vec{a}_t$ is the target location.

2.2 Co-articulation

The synthesis of more complex motor sequences requires the coupling of the adaptive control loop to a higher-level symbolic command. This link is realized by opening the model to a reference command. The most immediate approach is to specify directly at the command level a sequence of targets in the Cartesian space. But it does not allow to realize coarticulation which consists in anticipating movements according to the context. This means that at each iteration step, the variations of the angular coordinates of the effector system should depend on the previous movements as well as on the incoming movements. A way to deal with this co-articulation effect consists in taking into account the influence of targets from the near past and the near future. This can be achieved if the error function *E* is modified so that it becomes a weighted sum of elementary costs, each cost being activated at each target occurrence in the sequence:

$$grad(E(\vec{a},\vec{a}_t,t)) = \sum_{j=i-1}^{i+1} \lambda_j(t)(\frac{\partial M}{\partial \vec{q}})(\vec{a}_j - \vec{a}_{t_j}) \qquad (2.2)$$

with $\lambda_j(t) = K.e^{-\frac{(t-t_j)^2}{\tau_j}}$

This modified cost function allows the model to modify the articulatory configuration according to the temporal context. In particular, some articulators may be pre-positioned in order to reach the subsequent targets. The co-articulation is also a way to concatenate small movements with smooth transitions.

3 Control of voluntary hand-arm gestures

The control and the animation of two hand-arm systems have been studied. Each kinematic chain is driven by a sensory-motor model, as described in the second section. From real kinematic signals representing the trajectory of the arm end-point, we extract discrete spatio-temporal targets through a manual inversion process. Then the gestural command is described through a language which uses the main parameters of the Sign Language gestures, and is directly translated in a sequence of spatio-temporal targets driving the low-level generation system. A high-level specification of gestures is proposed [3-4], which produces automatically and in real-time complex and realistic hand-arm motion.

3.1 Low-level control

Arms are represented by geometric articulated models, with seven degrees-of-freedom and are controlled by targets in the cartesian space. Each finger of the hand is represented by an articulated chain with four degrees-of-freedom, and driven by a similar closed-loop system, with targets expressed in the angular space (configuration targets).

3.2 Synthesis of Sign-Language gestures

3.2.1 Gesture Command specification

Gestures are specified from gestural high-level commands which rely on the description of the French Sign Language (FSL) and on a discrete representation of the space around the signer.

The command is composed of a set of discrete targets which can be either spatial positions or angular configurations. Spatial targets are mainly used for the specification of the arm’s movements and configuration targets are used for hand shapes control.

The motion is decomposed in terms of elementary motion units. These units control the two hands and arms at different levels: the hand shape (the *configuration*), the arm’s motion (the *movement*) and the hand *orientation*. At a higher level, they are combined to obtain a movement involving an arm and its hand. Two more levels allow us to specify more complex gestures involving the two arms and the two hands (including motion of the fingers). This structured command leads to a coordinated movement of the upper limbs.

We can add elements of synchronization which refine the motion’s coordination between the different articulated bodies involved in the gesture.

3.2.2 Simulation and validation

The above system, called the GeSSyCa system, has been simulated and validated in two ways. First, the perceptive quality of the generated gestures have been evaluated, during a qualitative validation process. The aim of this work was to verify that the synthetic gestures looked natural from a perceptive point of view.

In addition to this process, a quantitative validation was performed, by confronting the data coming from the animation engine to real gestures data. This confrontation has been achieved by direct comparison between natural and artificial data, and also by using psychomotor laws such as the Fitt's law [6] or the "two-third" law [7].

In order to compare synthetic an real gestures, a corpus of gestures has been built. This corpus is based on movements recorded using *Flock Of Birds* sensors system from *Ascension Technology*. It contains recordings of a set of primitives which are the most frequently used in FSL. Each primitive is performed two times with three amplitudes, by two different subjects. Some additional gestures have been recorded to validate the co-articulation capabilities of our animation engine.

Comparison between synthetic data coming from the animation engine and real data has been mainly performed via speed profiles. Only some examples of the results are presented below. Other results can be found in [4].

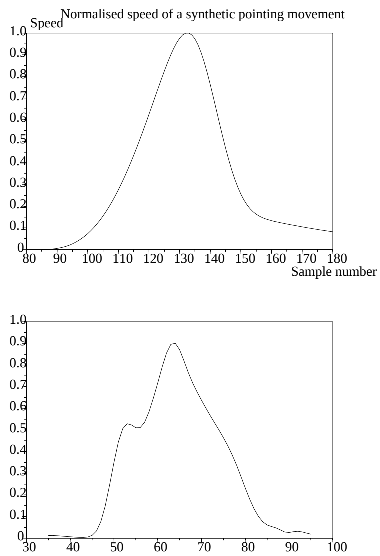

Fig. 1 Pointing gestures’ normalized speed profiles. In the upper curve, data come from a synthetic gesture, in the lower curve data come from real movement.

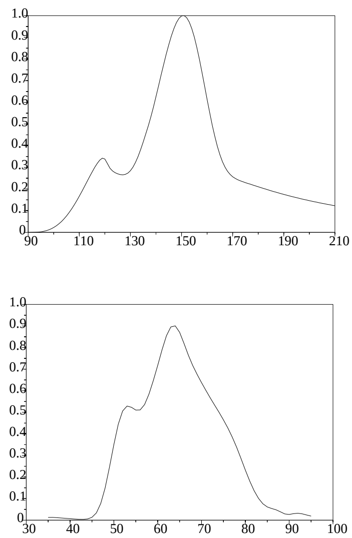

Fig. 2 Normalized speed profiles for curved movements. Synthetic gesture is on the upper curve, real gesture is on the lower.

Results from Viviani [7] have been used to compare both speed profiles and the ratio $V/R^{1/3}$, where V is the tangential velocity and R the radius of curvature. This ratio has been computed from normalized data. Curves are showed in figures 1 and 2.

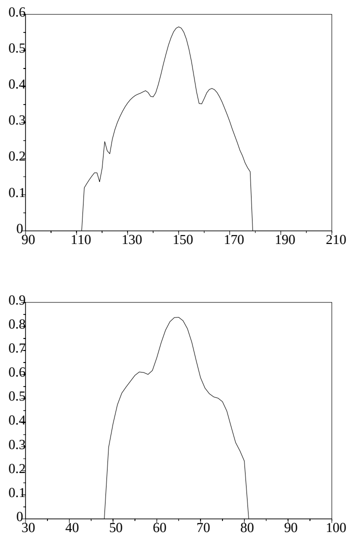

Fig. 3 $V/R^{1/3}$ for curved movements. Synthetic data is on the upper curve.

As can be observed above, the signals profiles are rather close. This shows the quality of the produced movements.

In addition, Sensory-Motor model's ability to link gestures to each others has been studied. We have verified that the animation engine can automatically append a gesture to another without visible transition. This is possible because the model treats coarticulation at a low level: because gesture commands are composed of targets, and thus appending a gesture to another is the same than generating a gesture composed of all the targets of the different gestures. The main feature is that the coarticulation does not require an external intervention to blend the movements in space or in time, as it is done in the approaches using pre-recorded movements.

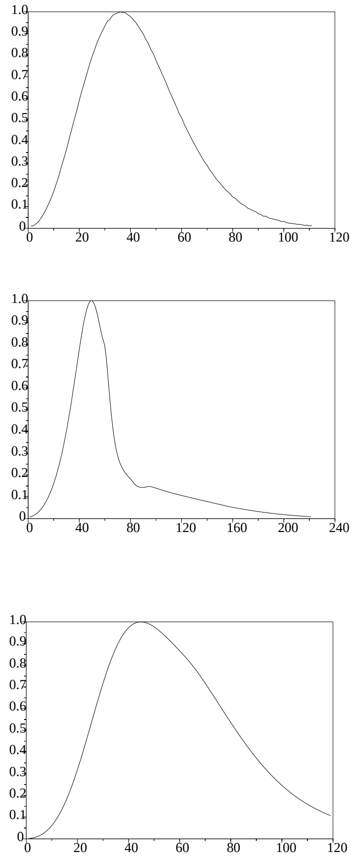

Fig. 4 Normalized velocity profiles of, respectively from top to bottom, a curved movement, a line movement and a another curved movement

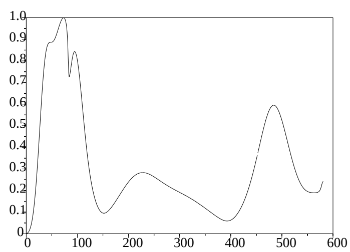

Fig. 5 Normalized velocity profile of the concatenation of three different movement primitives.

To illustrate this feature, we have concatenated three movement primitives: a curved forward movement, followed by a backward line movement, and a forward curved movement. Velocity profiles of each primitive taken separately are regrouped in figure 4. The velocity profile of the three primitives concatenation is showed in figure 5. As we can see, the concatenation produces a continuous movement with no visible transition.

The signals captured on real movements verify, under specific conditions, experimental laws which characterise invariant properties of the human motor performance. Among these laws, we may retain the

Fitt's law which expresses for simple pointing gestures the duration to reach a target *T* in function to the distance *D* and the accuracy *W* of the movement

$$T = a + b.\log\frac{2D}{W} \qquad (3.2)$$

a and *b* being constants.
The figure 6 illustrates the Fitt's law.

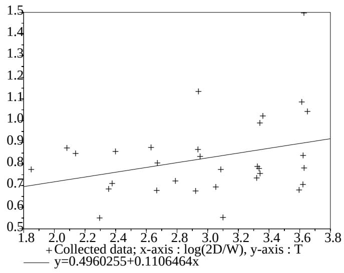

Fig. 6 On this figure, data coming from the model are represented by the crosses. The line has been calculated from these data by linear regression

4 Control of locomotion

The approach described here assumes that a locomotion movement, like walking, results from a complex Sensory-motor tasks combination. This composition involves a set of location or angular targets linked each other by temporal constraints. Two levels of reactivity arise from this approach : the first level is provided by the Sensory-Motor model in which sensory feedback data are used to continuously update articulatory parameters. The second level of reactivity is a planification level characterized by adaptive motor programs which have the ability to modify the control strategy according to reactions of the environment transmitted by the way of discret events. This last level is dedicated to the selection of the successive actions and the synchronization constraints. Within the control of complex articulated systems, motor programs which use the location targets are defined and translated into finite state machines.

4.1 Low-level control of poly-articulated systems

The generation model is composed of a set of Sensory-Motor servo-loops. Each of these servo loops has access to a specific kinematic chain, during the motion execution. The principe of this modelization is presented in figure 7. Length of limbs, degrees-of-freedom of each articulator and limit angular positions have been extracted from [8] and [9].

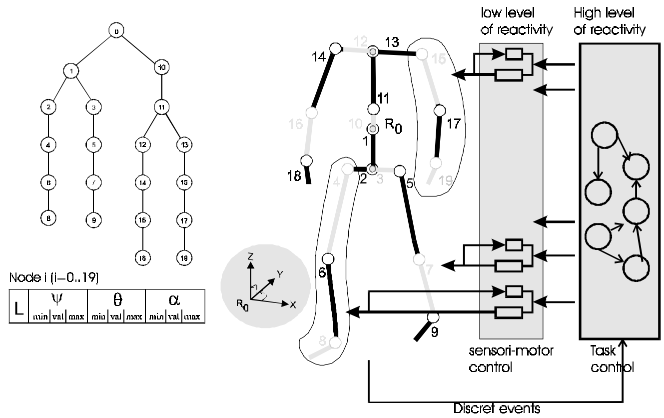

Fig. 7 The human body is represented by a hierarchical kinematic chain. The control of the motion involves two levels of reactivity.

4.2 From motor programs to movement

A motor program is a central representation of a motor ability previous to a motor performance. It can specify in a global strategy how to program different actions at different times.
The model of motion generation is driven by control variables provided by an automata. These control variables can be spatial targets (key-positions of the end-point of the articulated chain) or angular targets (vector of angular components for all the articulators of an articulated chain). The output variables which interact with the automata and influence the behavior of this automata are events generated by the generation model (reachable target, ellapsed duration, etc.) or events from the environment (collision, etc.).

4.3 Methodology of the motion conception

In this study, we assume that an automatic motion could be represented by the way of a set of Sensory-motor tasks, in our case defined by a vector of spatial or angular targets. The spatio-temporal specification of a motor program, for a walk cycle, is achieved by the extraction of a few targets from a real motion and the identification of the corporal segments on which the targets are applied.
A specification method has been proposed to elaborate the task program that will be executed by the generation system in [10]. The method expresses admissible behaviors of tasks according to the events which occur. These tasks constructions influence on the one hand the realism of the motion, and on the other hand the reactivity of the articulated system. A specific language, called Reactive Language, is used to express the temporal relations and the synchronization between tasks by the way of particular parallel and sequential operators.

4.4 Simulation and validation

Only six targets for the lower-limbs and four targets for the upper-limbs are used for this composition. The qualitative analysis of the motion is presented below.

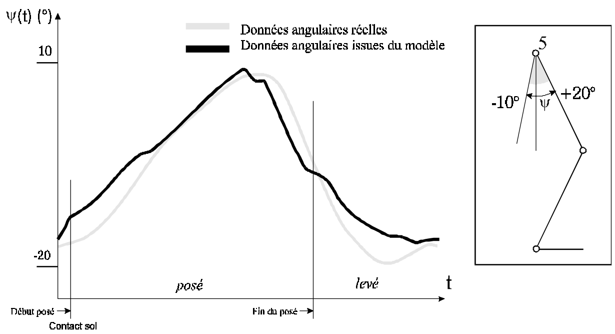

Fig.8 Angular variations at the left hip compared on a real motion

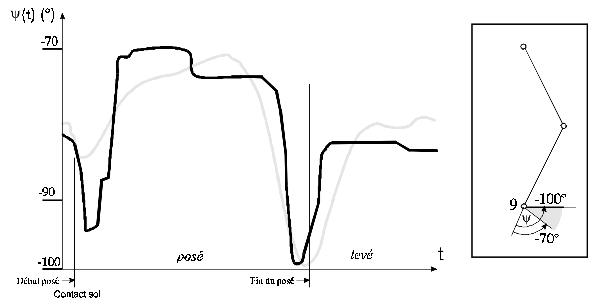

Fig. 9. Angular variations at the left ankle compared on a real motion

The low number of targets involved in the specification and the realism of the motion confirm the economy of the motion representation.

5 Conclusion

A Sensory-Motor approach has been presented here, which is applied to the simulation of human motion. From current sensory information measured in the observation space, a model is proposed which calculates the current state variables controlling the articulated chain. The simulation system is based on the assembling of several closed-loop models, each one being associated to an articulated chain. High-level gestural commands are then described exploiting the decomposition of motion in terms of elementary units of action. They are traduced in terms of a sequence of spatio-temporal targets which express goals to reach and drive the generation system. This one is composed of a set of servo-loops. Two studies have been carried out : one concerns the production of upper-limb movements and in particular the generation of Sign Languages gestures. These gestures are composed of elementary motion primitives using SL description parameters. A high-level language has been developed which specifies the synchronization and the coordination of the motion. The second study, which concerns automatic motions production, is applied to the human walk. The method proposes, by the way of a specific language called reactive language, to extend the use of the Sensory-Motor model to a complex human articulated body. Two validation processes have been carried out: the qualitative evaluation has given good results from a perceptive point of view: we can observe a good degree of realism in the produced animations. The quantitative validation process, which consists in comparing the output kinematic data with data measured from real motion gives satisfactory results. These validation processes will be carried out in the near future.

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