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Human Spatial Attitude Control by Means of Zero Momentum Turns

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This work proposes a methodology for the automatic control of the angular orientation of a multibody system based upon the preservation of its angular momentum. The control strategy used is hierarchical and decentralized arranging the control stages in levels of attributions and complexity. At a lower level the controllers are responsible for handling each of the multibody degrees-of-freedom forcing them to follow prescribed reference motions through the use of error feedback. Middle level controllers coordinate the lower level controllers so that each of the multibody sub-systems achieve prescribed reorientation. These reorientations are defined by a higher level controller with the final objective of reorienting the complete multibody system to reach a different attitude. The underlying control strategy of the multibody is applied to the human spatial attitude in a zero gravity environment. Here, the biomechanical model used is defined such a way that all biomechanical joints are described by joints with one or two degrees-of-freedom, to which lower level controllers are associated. A formulation based on natural coordinates is used to describe the multibody system due to its ease of representing the biomechanical features of the model. The physiological data for the biomechanical model is described in a database where information for different subjects is available. In this form the application case is not dependent in a particular human subject but can be used in general cases. The control laws associated with the controllers are parametrically adjusted for the biomechanical model under analysis. The results obtained are finally discussed in face of the modeling assumptions made and control laws used.

Keywords: *Biomechanical Models, Joint Motion Range, Hierarchical Control, Optimal Motion.*

1. INTRODUCTION

Some natural and artificial systems, made of multiple rigid bodies that have their relative motion constrained by kinematic joints, are required to reorient their spatial attitude without the application of any external force or moment. Space satellites with movable antennas, astronauts, divers or a falling cat are examples of these type of systems. The cat self-aligning reflex is an example of how a biomechanical system can achieve an prescribed orientation only by changing the relative orientations of its segments, preserving in this form the momentum [1,2]. The same type of zero momentum turns can be developed by the diver, with a succession of turns and somersaults, or by an astronaut in a zero gravity environment. This case deserved the attention of Kane and co-workers [3,4] and of Passerello and Huston [5], who in a series of contributions described the typical maneuvers necessary to achieve a desired orientation and demonstrated experimentally their feasibility.

In this work, a strategy for the angular reorientation of multibody systems using zero momentum turns is proposed. The system, a biomechanical model, is described using natural coordinates [6]. This type of coordinates lead to equations of motion that have a lower degree of nonlinearity than the Cartesian coordinates [7] making it possible to introduce kinematical joints without increasing the number of kinematic constraints. The biomechanical model used is composed of 18 biomechanical segments represented by a total of 33 rigid bodies whose physical characteristics assuring biofidelity, are tied to a human anatomic database. Furthermore, this models has the relative segment rotation penalized if they achieve physically unfeasible relative orientations [8,9]. The control of the angular reorientation is a complex task as the biomechanical model is a large scale system. Therefore a methodology suitable to this large scale system is necessary [10]. A decentralized and hierarchical control is used with three stages of controllers of increasing complexity. The execution of a large number of maneuvers is then planed using artificial intelligence concepts [11].

2. BIOMECHANICAL MODEL

The description of the biomechanical multibody system, used here, is based on natural coordinates [6]. In this formulation all bodies are represented by sets of points and unit vectors. Kinematic constrains arise naturally by sharing points and vectors between different bodies and by imposing constant distances and angles in the definition of each body. Figure 1 shows the types of rigid bodies and joints being the corresponding algebraic constrains shown on table 1.

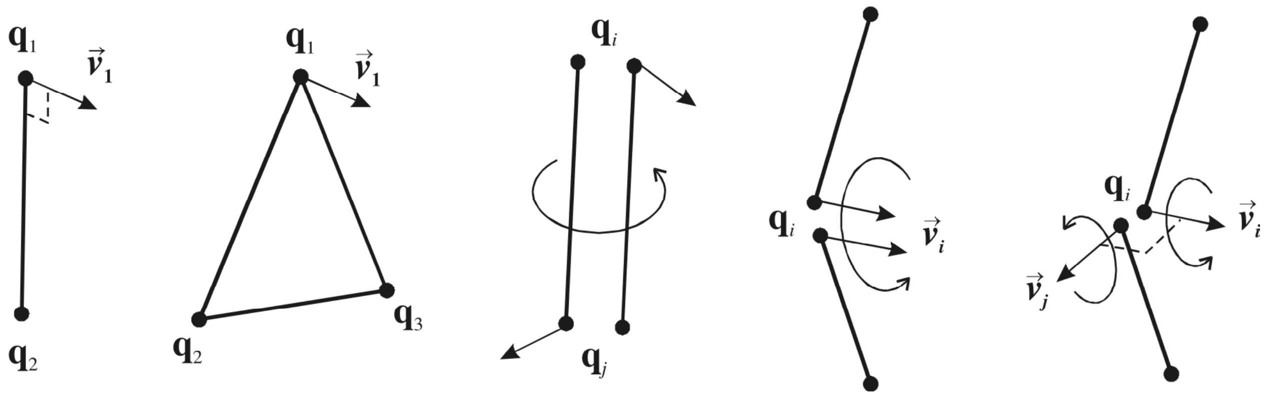

Figure 1: Rigid bodies defined by: (a) 2 points and 1 vector, (b) 3 points and 1 vector. Joints: (c) Revolute joint obtained by sharing 2 points; (d) Revolute joint obtained by sharing 1 vector; (e) Universal joint obtained by sharing 1 point and imposing the orthogonality between 2 vectors

Table 1
Definitions and Constrains used in the Model

Constant distance between two points	$\mathbf{r}_{ij}^T\ \mathbf{r}_{ij} - L_{ij}^2 = 0, \mathbf{r}_{ij} = \mathbf{q}_j - \mathbf{q}_i$	(1)
Constant angle between a vector a two point line	$\mathbf{r}_{ij}^T\ \mathbf{v}_i - L_{ij}\quad \cos(\phi) = 0$	(2)
Unit vector	$\mathbf{v}_i^T\ \mathbf{v}_i - 1 = 0$	(3)
Additional constrain in universal joint	$\mathbf{v}_i^T\ \mathbf{v}_j = 0$	(4)

The biomechanical model is represented as a collection of rigid bodies constrained by kinematic joints and acted upon by external forces. Its equations of motion are described by:

$$\mathbf{M}\ddot{\mathbf{q}} + \Phi_{\mathbf{q}}^T \lambda = \mathbf{g} \tag{5}$$

Representing the coordinates of the points and vectors by $\mathbf{q} = [\mathbf{q}_1^T,..., \mathbf{q}_n^T]^T$, where $\mathbf{q}_i = [\mathbf{r}_i^T, \mathbf{r}_j^T, \mathbf{v}_i^T, \mathbf{v}_j^T]^T$ its second time derivative $\ddot{\mathbf{q}}$ is the vector of the Cartesian accelerations. **M** the global mass matrix, **g** the vector of the generalized external forces, **l** the vector of Lagrange multipliers and $\mathbf{F}_\mathbf{q}$ is the Jacobian matrix. Details on the formulation of multibody systems using the natural coordinates can be found on the work by Jalon and Bayo [6].

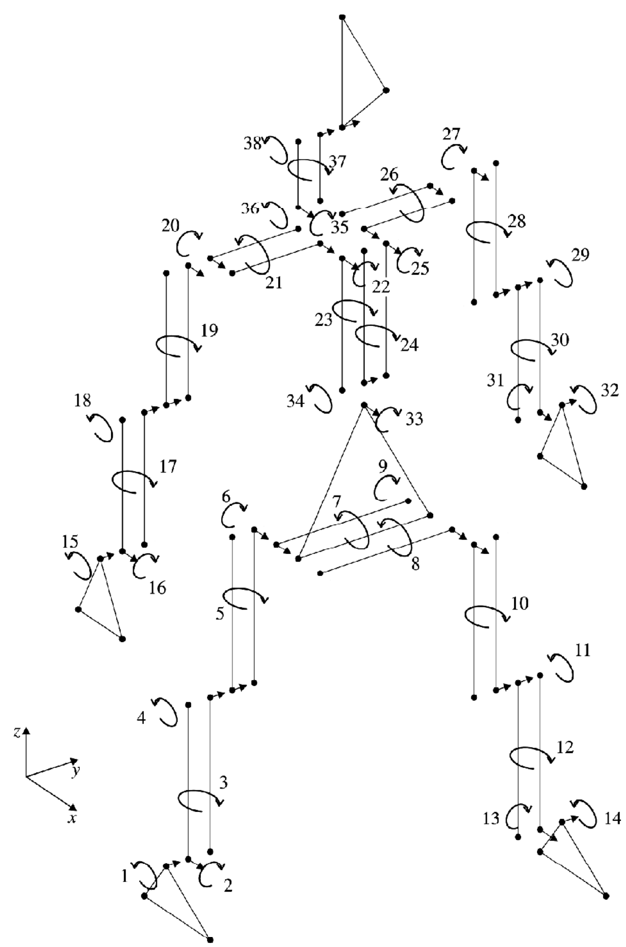

Figure 2: Biomechanical model used showing all the bodies, points, vectors and actuators

3. CONTROL OF THE BIOMECHANICAL SYSTEM

Due to the high complexity of the multi-body biomechanical system the use of global control through full state feedback is not recommended [10]. The control scheme used here is decentralized and hierarchical. Three levels of control are defined: low level control actuates on the controller of each joint using a variable gain PD controller; the intermediate controller defines trajectories

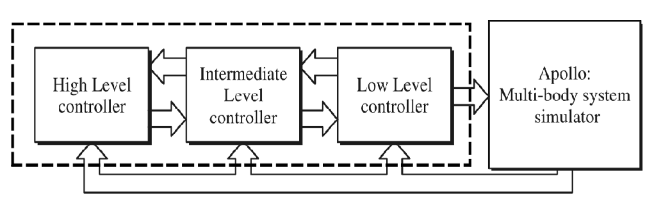

Figure 3: Block diagram of the control structure

that the local controllers have to ensure; the high level controller chooses the best set of maneuvers that minimize an energy function, as described in Figure 3.

3.1. Low Level Controllers

Using the joint coordinate method [7] the biomechanical system is represented by a base body connected to other rigid bodies by kinematic joints. The base body has 6 d.o.f., each revolute joint has 1 d.o.f. and each universal joint has 2 d.o.f. Each joint is controlled by a independent variable gain PD controller [12]. Each pair of bodies is connected by a joint actuated by a single independent control torque T_{ij} which is applied through the joint. Ignoring Coriolis, centrifugal and reaction forces, results in

$$J'_{ij}\ddot{\theta}_{ij} = T_{ij} \tag{6}$$

where

$$J'_{ij} = \frac{J_i J_j}{J_i + J_j} \tag{7}$$

$$\theta_{ij} = \theta_j - \theta_i \tag{8}$$

where θ_{ij} is the relative angle between adjacent body segments and J_i is the inertia moment of body i and all the attached bodies relative to the joint axis, as seen in Figure 4.

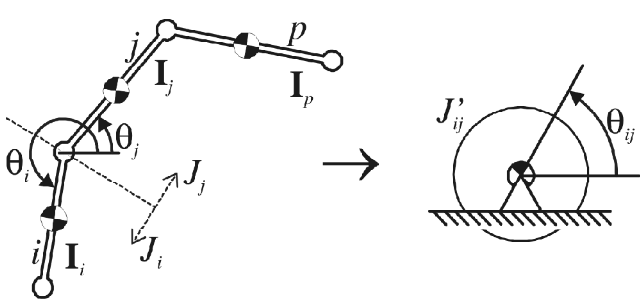

Figure 4: Simplifications assumed in the model. The doted arrows represent the bodies included in the calculus of J_i and J_j

The control law applied is proportional-derivative (PD) on angular position:

$$T_{ij} = -k_{ij}^P\left(\theta_{ij} - \theta_{ref\ ij}\right) - k_{ij}^D\,\dot{\theta}_{ij} \tag{9}$$

The superscript D stands for *derivative* and P stands for *proportional* over constant k and $\theta_{ref\ ij}$ is the desired angular position on the joint ij imposed by the intermediate controller.

The simplified model of a system with feedback is described by the second order linear differential equation given by

$$J'_{ij}\,\ddot{\theta}_{ij} + k_{ij}^D\,\dot{\theta}_{ij} + k_{ij}^P\theta_{ij} = k_{ij}^P\theta_{ref\ ij} \tag{10}$$

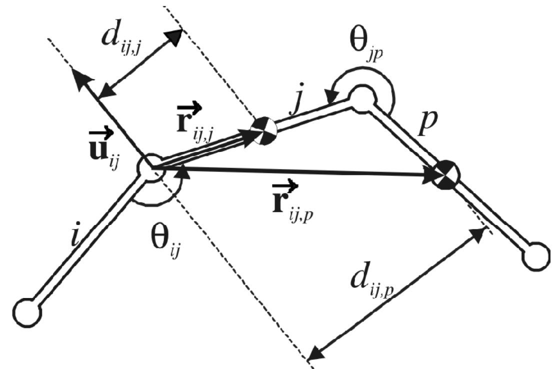

Figure 5: Illustration of parameter involved in the calculus of the moment of inertia on axis uij

A more common form of presenting the equilibrium equation for a second order system is

$$\ddot{\theta}_i + 2\zeta_i\,\omega_{ni}\,\dot{\theta}_i + \omega_{ni}^2\,\theta_i = 0 \tag{11}$$

which by comparing equations (10) and (11) leads to the definition of the damping coefficient ζ_{ni} and natural frequency ω_{ni} as

$$\zeta_i = \frac{k_{ij}^D}{2\omega_{ni}J'_{ij}} \quad ; \quad \omega_{ni}^2 = \frac{k_{ij}^P}{J'_{ij}} \tag{12}$$

Note that the choice for the damping coefficient is particularly important as it leads to under, critically or over-damped systems. Solving second order differential equation and choosing k_{ij}^D so that the response is slightly over damped results in the following control law:

$$T_{ij} = -J'_{ij}\omega_{ij}^{\;2}\left(\theta_{ij} - \theta_{ref\ ij}\right) - \alpha\sqrt{2}J'_{ij}\omega_{ij}\dot{\theta}_{ij}, \quad \alpha \geq 1 \tag{13}$$

where ω_{ij} is the angular frequency of the controller and α is the over-damping term. Note that the angular frequency of the controller, which needs to be adjusted for each particular joint, defines the stability and the quickness of response of the system with feedback. Due to the chain configuration of the multibody system the moment of inertia calculated on one joint changes if a preceding body connected by a different joint alters its center of mass. Referring to figure 5, the update of the moments of inertia, required in each time step, is calculated by [13]

$$J_i = \mathbf{u}_{ij}^T\left\{\sum_{k\in S_i}\mathbf{A}_k^T\,\mathbf{I}_k\,\mathbf{A}_k\right\}\mathbf{u}_{ij} + \sum_{k\in S_i} m_k\,d_{ij,k}^2 \tag{14}$$

where $\mathbf{u}_{ij}$ is a unitary vector collinear to the axis of the joint ij, S_i is the set of bodies that attached to body i by other joints than ij, $\mathbf{A}_k$ is the coordinate transformation matrix from the local body referential to the global referential and d_{ijk} is the distance between the axis of joint ij and the center of mass of body k given by

$$d_{ij,k} = \left\| \mathbf{r}_{ij,k} - \left(\mathbf{r}_{ij,k}{}^{T} \mathbf{u}_{ij} \right) \mathbf{u}_{ij} \right\|, \mathbf{r}_{ij,k} = \boldsymbol{\rho}_k - \mathbf{r}_{ij} \tag{15}$$

where $\mathbf{r}_{ij}$ is the spatial position of joint ij. Finally, a torque saturation law is defined

$$F_{ij}\left(T_{ij}\right) = \begin{cases} -T_{ij\max} & if \quad T_{ij} < -T_{ij\max} \\ T_{ij} & if \quad \left|T_{ij}\right| \le T_{ij\max} \\ T_{ij\max} & if \quad T_{ij} > T_{ij\max} \end{cases} \tag{16}$$

The controller action, including the feedback, is described by figure 6.

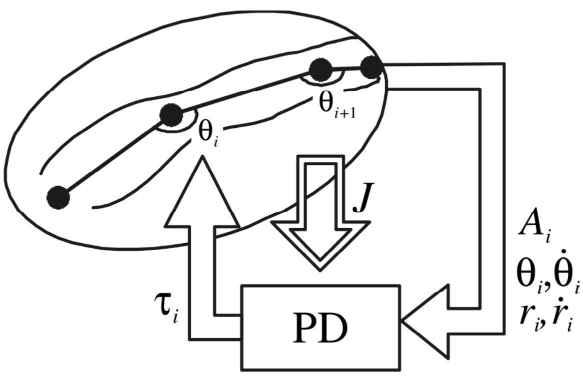

Figure 6: General representation of the low level joint controllers

At this point it is emphasized that the gains of the controllers are in fact adjusted for each new point of the trajectory due to the variations of the inertia moments. In order to avoid that the controllers develop a unrealistic moment a saturation moment is adopted for each controller, based on physiological reasoning.

3.2. Intermediate Controller

The intermediate control, after receiving from the higher level control the definition of the maneuver that the whole body is supposed to develop, defines for each local controlled the reference angle and a law for its variation. This controller has the complete description of the particular maneuver required and assures that they are properly developed. The functional scheme of the intermediate controller is briefly described in figure 7.

There are quite a good number of motion tasks that include zero-momentum turns. The self-aligning reflex of the cat or the alignment maneuver of a diver are some of the best known of these type of maneuvers. The sequence described in figure 8(a) illustrate the maneuvers involved in the self-alignment reflex of the cat, characterized by successions of torsion-bending tasks while in figure 8(b) the torsion tasks with changes in the inertia moments, associated with human body alignments, are described.

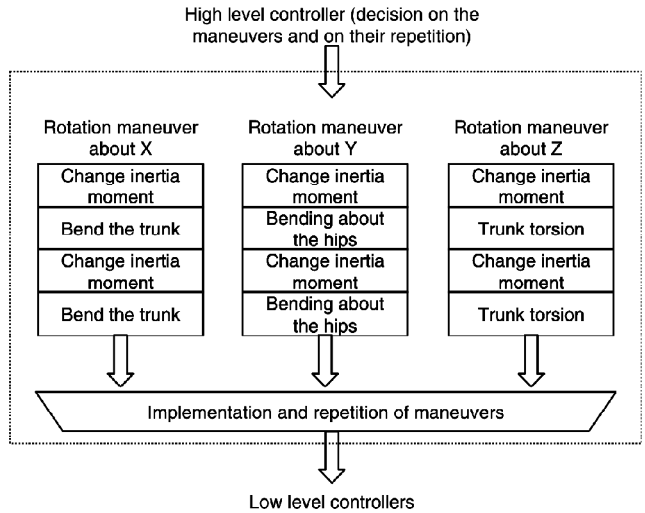

Figure 7: Schematic description of the intermediate level controller

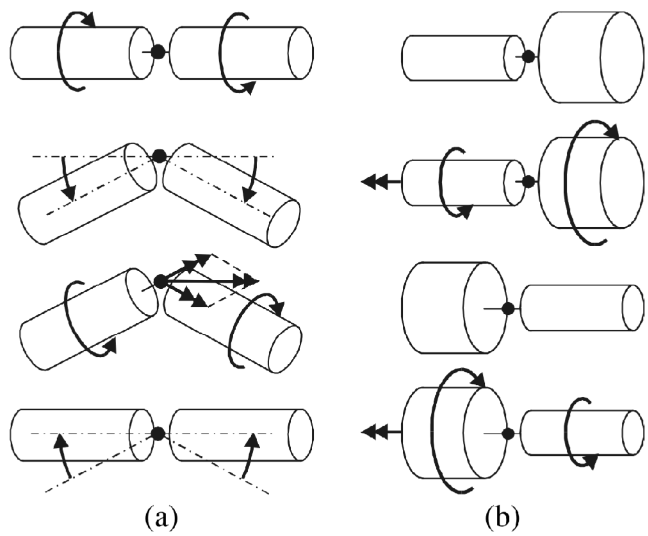

Figure 8: Maneuvers that involve zero-momentum turns: (a) torsion-bending as in the cat self-aligning reflex; (b) torsion with variation of the inertia moments

For each rotation maneuver an energy cost function must be defined. Since each zero angular momentum turn only permits a limited of angle of rotation, high angles, such as those illustrated in figures 9 through 11, require repetitions of the elementary zero angular momentum turn. The energy function associated to each axis is defined by:

$$\begin{aligned} & f_E\left(i,\theta\right) = d_i\left|\theta\right| + c_i\left(1 + \mathit{floor}\left(\left|\theta\right| / \theta_{\max i}\right)\right), \ i \in \left\{X, Y, Z\right\} \\ & \mathit{floor}(x) = n : n \le x \wedge x - n < 1 \ , \ n \in IN \end{aligned} \tag{17}$$

where c_i represent the cost due to alteration of moment of inertia, and $d_i|q|$ represents the cost due to torsion. Assuming the single body simplification, PD controllers and ideal actuators, the cost due to amount of torsion is linear. Figure 12 illustrates the energy cost function. It should be noted that the intermediate controller simply guarantees that the maneuver assigned by the high level controller is fulfilled, without regard for its cost. The choice of the actual maneuver that minimizes the cost function is done by the high level controller.

Figure 9: Zero angular momentum maneuvers illustrating a rotation in X axis

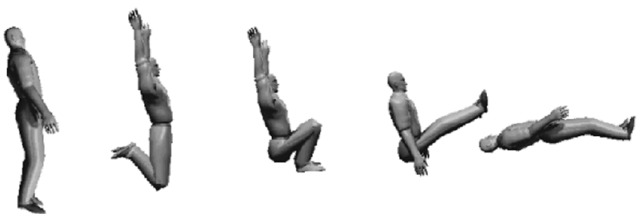

Figure 10: Zero angular momentum maneuvers illustrating a rotation in Y axis

Figure 11: Zero angular momentum maneuvers illustrating a rotation in Z axis.

3.3. High Level Controller

Any reorientation maneuver in space can be accomplished by performing a rotation, or a set of rotations, with respect to well-defined axes. Assuming that the goal is the reorientation a base body, then the rotation matrix ($\mathbf{M}_R$) for this body to achieve the goal is defined by the product of the desired orientation matrix ($\mathbf{A}_F$) by the initial orientation matrix ($\mathbf{A}_I$) transposed. The matrix $\mathbf{M}_R$ can by built using any set of rotational coordinates such as Euler parameters, Euler angles or Bryant angles

$$\mathbf{M}_R = \mathbf{A}_F.\mathbf{A}_I^{\,T} \tag{18}$$

$$S_R = \left\{ A \subset S_A : \forall B \subset S_A, \prod_{i \in \{A,B\}} \mathbf{M}_i = \mathbf{M}_R, \sum_{i \in A} f_E(i) \le \sum_{j \in B} f_E(j) \right\} \tag{19}$$

The problem consists on choosing the best set of 3D rotations S_R on the available set S_A, based on some energy functions $f_E(i)$, that return matrix $\mathbf{M}_R$. As shown before the rotations are defined on the principal axes of the base body, referred to by XYZ. Therefore, S_A is defined by:

$$S_A = \{(i, \theta),\ i \in \{X, Y, Z\}, -\pi < \theta \le \pi\} \tag{20}$$

Since any spatial rotation can be described by a sequence of three rotations $\#S_R = 3$, the number of permutations leading to different sets of rotations is 12.

The solutions adopted for the high level controller consists on the search of the minimal energy spend on rotations. The matrices of rotation about the principal axes are defined by:

$$\mathbf{M}_{(X,\phi)} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix}, \mathbf{M}_{(Y,\theta)} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix},$$

$$\mathbf{M}_{(Z,\psi)} = \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Since the product of 3 rotation matrices of the previous type returns a matrix with simple products of sine and cosine terms, extraction of the sets of angles for all axes permutations is straight forward. The periodicity of trigonometric functions results in 2 different solutions for each combination of rotations: if i, j, k are different

$$\mathbf{M}_{(i,\pi+\phi)}.\mathbf{M}_{(j,\pi-\theta)}.\mathbf{M}_{(k,\pi+\psi)} = \mathbf{M}_{(i,\phi)}.\mathbf{M}_{(j,\theta)}.\mathbf{M}_{(k,\psi)}; i, j, k \in \{X, Y, Z\} \tag{21}$$

or if $i = j \ne k \vee i \ne j = k \vee i = k \ne j$.

$$\mathbf{M}_{(i,\pi+\phi)}.\mathbf{M}_{(j,-\theta)}.\mathbf{M}_{(k,\pi+\psi)} = \mathbf{M}_{(i,\phi)}.\mathbf{M}_{(j,\theta)}.\mathbf{M}_{(k,\psi)}; i, j, k \in \{X, Y, Z\} \tag{22}$$

The high level controller results in the following algorithm:

1. Extract sets of angles from matrix $\mathbf{M}_R$ for the 12 combinations of rotations.
2. Use the periodicity to double de solutions of sets of angles.
3. Apply energy cost function to each set of angles.
4. Choose the set of angles that have minimum energy cost.

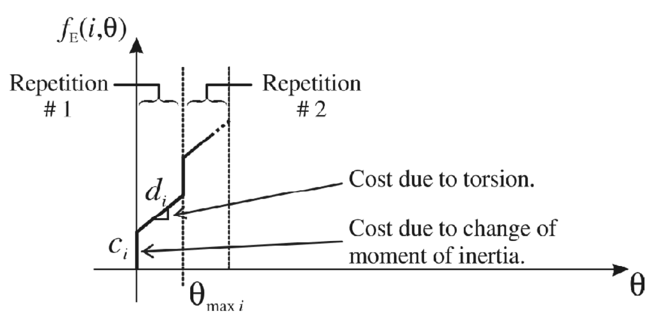

Figure 12: Energy cost function associated with zero angular momentum turns

This method has the advantage of easily providing the set of rotations that minimize energy. However the method is not yet developed for generic axes of rotation.

4. APPLICATION TO THE HUMAN BODY ATTITUDE IN ZERO GRAVITY

As an application of the methodology the spatial change of attitude of a biomechanical model in a zero gravity environment is selected. A model initially facing the X-axis is required to rotate 60º counter clockwise, resulting in the motion illustrated by Figure 13. The general purpose code APOLLO [14] is used. No particular effort has been made to use an optimized gain for the controllers. If the gain is increased the maneuvers proceed at a higher velocity, approaching what is perceived to be a reasonable speed of execution, but the time step of the integration scheme decreases. Consequently, the ratio between the computational time required to simulate the maneuver and the time simulated does not change in the same proportion of the increase of the gains. In setting up these gains the physiological characteristics of the human body model must be accounted for [15].

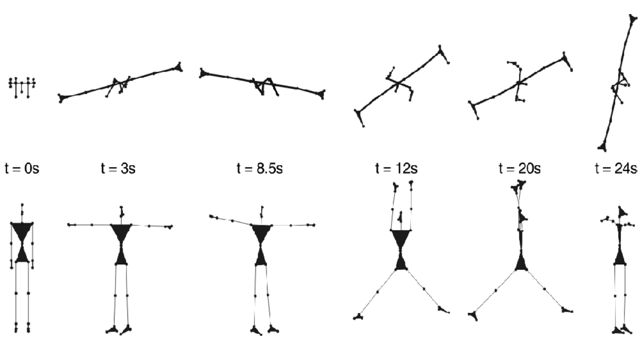

Figure 13: Initial, intermediate and final position of biomechanical model: top view; front view

In figure 14 the change of the angles due to the control strategy adopted are represented as a function of time. The corridors shown in the picture correspond to the range for which a particular low level controller is not active because the corresponding joint angle is in the neighborhood of the target. Figure 15 presents the evolution of the total moments of inertia about Z-axis for upper torso and the upper extremities of the biomechanical model and for the lower torso and lower extremities respectively. It is observed that the variation of the inertia moment of the lower torso and legs is more important that the variation of the upper torso inertia. As a consequence, the rotation of the lower torso is much smaller than the upper torso while the control is trying to reposition the biomechanical model. This result is described in figure 16.

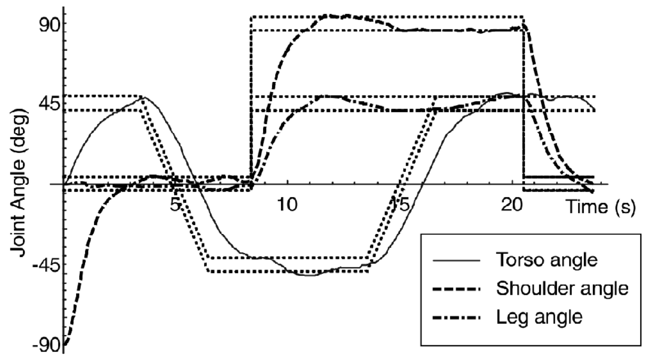

Figure 14: Change of angles during maneuvers for shoulder (joint 20 of figure 2), torso (joint 23) and leg (joint 6). The dotted lines represent the limits of the angles within which there is no active control

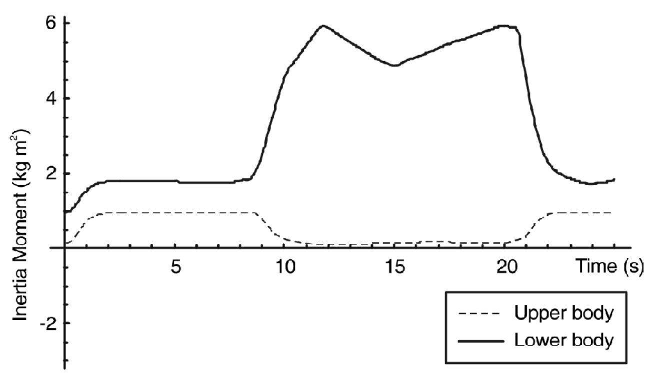

Figure 15: Variation of the upper body and lower body inertia moment about the Z axis

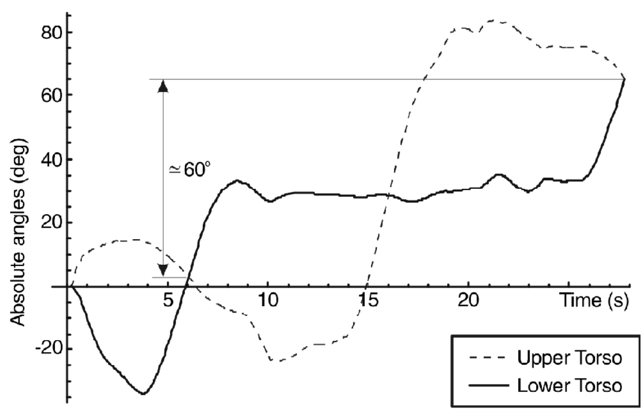

Figure 16: Evolution of the attitude upper and lower torso during the simulation

5. CONCLUSIONS

A methodology using a general multibody description of a biomechanical model, to which is applied a decentralized hierarchical control strategy, has been presented in this paper and applied to the attitude control of a biomechanical model in a zero gravity environment. The application shows that the use of the techniques described are feasible to achieve the reorientation of mechanical systems with efficiency and reliability in a systematic form. The sequence of individual motions required to complete each maneuver is closely followed by the individual biomechanical segments, as demonstrated by the simulation results. However, some further considerations must be taken into account in order to improve the application of the method to biological systems. The choice of the sequence of maneuvers outlined here is based on a look at table of available motions. Though this mimics the fact that the human being uses in fact a finite set of motion to execute any complex task it does not account for the optimization of these simple movements. Therefore, it is desirable to obtain the finite set of maneuvers contained in the table by some optimal criteria, which would correspond to the training and mechanization of the motion by the human subject.

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