Improved Kinematics Simulation Model of General Human and Humanoid Motion

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Abstract: Dynamic model developed for an advanced humanoid robot can be seen as a very useful tool for the dynamic analysis of human motion in different tasks (walking, running and jumping, manipulation, various sports, etc.) [1]. To this purpose we derived a general model and discussed a human-and-humanoid simulation system. The basic idea is to start from a human/humanoid considered as a free spatial system ('flier'). Particular problems (walking, jumping, etc.) are then seen as different contact tasks – interaction between the flier and various objects (being either single bodies or separate dynamic systems). The advantage of thus conceived system is its openness and the possibility of its upgrading and constant improving. On the basis of the previously obtained simulation results it could be concluded that it is possible to introduce certain kinematic improvements in the model, yielding better dynamic characteristics of the system.

Keywords: Humanoid, dynamics, contact task, impact, human motion, Zero-Moment Point (ZMP)

1 Introduction

The approach to such a challenging simulation task requires a special analysis of the initial state of the system. The simulation model has to satisfy some basic kinematic and dynamic properties. It must possess a sufficient number of general characteristics, so that the basic kinematic and dynamic properties in the future diverse simulated sporting situations could be comparable with the real systems. On the other hand, the basic model should also possess a sufficient amount of simplified characteristics, to allow relatively simple and fast simulation giving the simulation results which still reflect most important phenomena and effects that are comparable with real systems. Hence we consider a flier as an articulated system consisting of the *basic body* (the torso) and several *branches* (head, arms and legs), as shown in Fig. 1 [2-4].

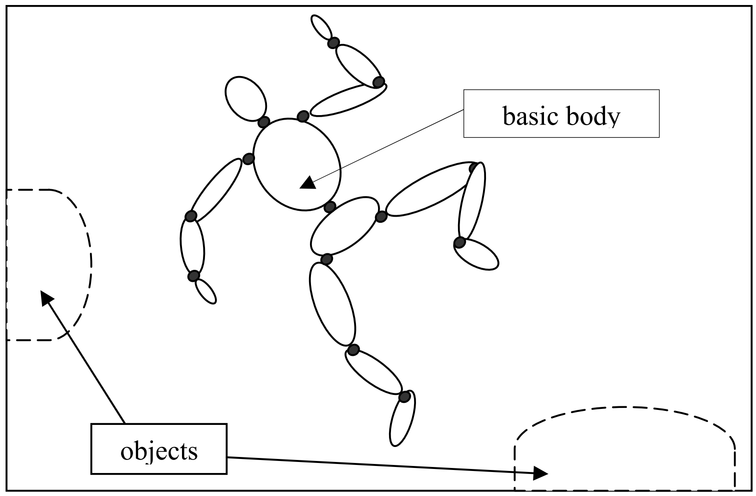

Figure 1
Unconstrained system - free flier

Let there be n independent joint motions described by joint-angles vector $q = [q_1, \cdots, q_n]^T$. (The terms *joint coordinates* or *internal coordinates* are often used.) The basic body needs six coordinates to describe its spatial position: $X = [x, y, z, \theta, \varphi, \psi]^T$, where x, y, z defines the position of the mass center and θ, φ, ψ are orientation angles (roll, pitch, and yaw). Now, the overall number of degrees of freedom (DOFs) for the system is $N = 6 + n$, and the system position is defined by

$$Q = [X, q]^T = [x, y, z, \theta, \varphi, \psi, q_1, \cdots, q_n]^T \quad (1)$$

We now consider the drives. It is assumed that each joint motion q_j has its own drive – the torque τ_j. Note that in this analysis there is no drive associated to the basic-body coordinates X [1]. The vector of the joint drives is $\tau = [\tau_1, \cdots, \tau_n]^T$, and the augmented drive vector (*N*-dimensional) is $\mathrm{T} = [0_6, \tau]^T = [0, \cdots, 0, \tau_1, \cdots, \tau_n]^T$.

[1] This is a real situation with humans and humanoids in 'normal' activities. However, humans are already engaged in space activities and humanoids are expected soon [9-11] (actions alike repairing a space station, etc.). In such activities, reactive drives are added, and they are attached to the torso. The proposed method for simulation can easily handle this situation.

The dynamic model of the flier has the general form:

$$H(Q)\ddot{Q} + h(Q,\dot{Q}) = \mathrm{T} \qquad (2)$$

or

$$\begin{aligned} H_{X,X}\,\ddot{X} + H_{X,q}\,\ddot{q} + h_X &= 0 \\ H_{q,X}\,\ddot{X} + H_{q,q}\,\ddot{q} + h_q &= \tau \end{aligned} \; . \qquad (3)$$

Dimensions of the inertial matrix and its submatrices are: $H(N \times N)$, $H_{X,X}(6 \times 6)$, $H_{X,q}(6 \times n)$, $H_{q,X}(n \times 6)$, and $H_{q,q}(n \times n)$. Dimensions of the vectors containing centrifugal, Coriolis' and gravity effects are: $h(N)$, $h_X(6)$, and $h_q(n)$.

2 Simulation: Example 1

2.1 Configuration and the Task

We consider a human/humanoid model having n = 20 DOFs at its joints, shown in Fig. 2. This can be seen as a humanoid or an approximation of human body [5-8]. Definition of the joint (internal) coordinates, vector $q = [q_1, \cdots, q_n]^T$, is presented as well. Here, we only mention that its total weight (mass) is 70 *kg*.

The task is selected as a specific action in handball. A player jumps, catches the ball with his right hand, and throws the ball while still flying. The ball should hit the ground in front of the goalkeeper in order to trick him [2-4]. In a realistic situation, this would be a learned pattern. So, we consider this player's motion as a reference and try to realize it. As stated above, for the purpose of simulation the reference motion was not measured but synthesized numerically. (in Figs. 5, 6 and 7). The ball mass is 450 g and the radius is 9.5 cm.

The human/humanoid is equipped with actuators at its joints and the control system that will try to track the reference motion. Among different control strategies, we implemented local PD regulators,

$$\tau_j = K_{Pj}(q_j - q_j^*) + K_{Dj}\dot{q}_j\,, \; j = 1, \cdots, n\,,$$

where q_j is the actual value of a joint coordinate, and $q_j^*(t)$ is its prescribed reference. Such simple control is considered appropriate since dynamics, and not control, is the key point of the paper.

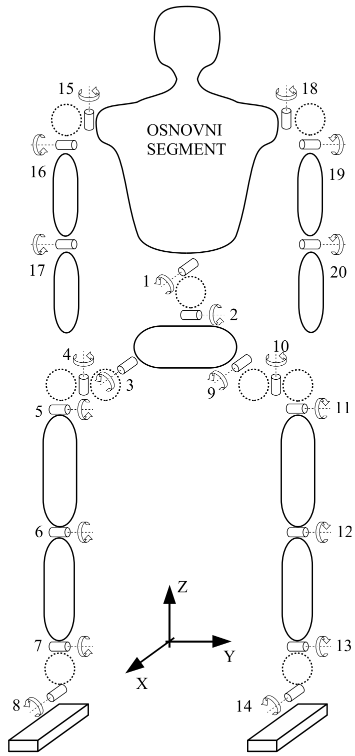

Figure 2
Adopted configuration of the human/humanoid

The improvement with respect to the previous results is the fact that the simulation does not expect contact (the condition when one of the coordinates is zero) but, on the basis of the ball path and position of the body and kinematics of the motion, the simulation predicts the site of the contact of the hand and the ball. Namely, this is a more realistic situation than is the case when the contact is constantly expected, which, generally, may not be realized at all because of the disturbance in the system. On the other hand, such an approach is more realistic in sporting activities because the top players do not wait for the event to occur but predict the site and situation of the desired event, and plan all their actions according to the preconceived (envisaged) situation.

By the proposed improvements the simulation system is somewhat simplified as there is no constant expectation of contact realization but the simulation runs normally without checking to the moment when the event should take place and then the checking system is activated to verify whether the expected event occurred.

2.2 Analysis of the Results

Figure 3 shows the realized motion in the case of a fairly trained player. His intention (and reference) was to jump, catch the ball, swing with his hand, and throw the ball. According to Fig. 3, his attempt was successful. Let us analyze the player's motion in more detail. One can observe several phases of the motion:

- ► ***Phase 1 – takeoff.*** Both legs are in contact with the ground accelerating the body upward (Figs. 3a,b,c). This phase ends at 0.108*s*. At this instant the legs lose the contact with the ground (Fig. 3c).

  ● From the viewpoint of mechanics the flier (player in this example) has two contacts with an immobile object – both feet are on the ground. A closed chain is formed. Each contact restricts all six relative motions and accordingly creates six reaction forces/torques (twelve reactions in total).

- ► ***Phase 2 – free flight towards the ball.*** The player is moving (flying) up while expecting the contact with the ball (Figs. 3d,e,f). The right hand establishes the contact with the ball (catches the ball) at 0.183 *s* (instead 0.224 *s* in the previous work) and Phase 2 ends (Fig. 3).

  ● In this phase, there is no contact with any object; a true flier is considered. The system has a tree structure (no closed chain).

- ► ***Phase 3 – impact.*** The contact of the player's hand and the ball always involves an impact effect. It occurs at 0.183 *s* (Fig. 5f). For the current analysis we assume an infinitely short impact.

  ● The collision between the hand motion and the motion of the object (the ball) will cause an impact. Since the contact will restrict all six relative coordinates, the impact is characterized by a six-component momentum. The infinitely short impact generates infinitely large reactions and, accordingly, the instantaneous change in the system velocities. The momentum still has a finite value.

- ► ***Phase 4 – swinging and throwing.*** The player swings with his right arm (Fig. 3g) and throws the ball (Fig. 3h). The ball leaves the player's hand at 0.318 *s* and Phase 4 ends.

  ● From the point of view of mechanics, a contact is established between the flier's hand and an external mobile object (the ball). The contact restricts all six relative motions and produces six reaction forces/torques. The contacted object is a separate system (body) that has its own dynamics, now being influenced by the flier (and vice versa).

- ► ***Phase 5 – falling down.*** The ball and the player now move separately (Figs. 3i,j,k,l). The ball has its own trajectory, to hit the ground in front of the goal. The player is falling down (free flying) until landing (he touches the ground at

0.481 s, Fig. 3 l). The landing is performed correctly, so that the player will not overturn.

● Since there is no contact, a truly free flier is considered again. This lasts until a new impact establishes the contact of the flier's right foot and the ground.

Our simulation stops when the player touches the ground.

3 Simulation: Example 2

3.1 Configuration and the Task

The player configuration used in Example 1 is modified by introducing more complex arms. The new configuration of arms is shown in Fig. 4. So, the number of DOFs at the player's joints is now $n = 28$. This was necessary in order to make the player capable of handling the new task (involving closed chain).

The task is selected as a specific action of a goalkeeper in soccer. The ball is moving towards the goalkeeper; he jumps, catches the ball with both hands, moves it towards his waist, and finally lands while holding the ball all the time. In a realistic situation, this would be a learned pattern; we consider this player's motion as a reference and try to realize it by using local PD regulators (as explained in Example 1). For this simulation the reference motion was not measured but synthesized numerically. The ball mass is 450 g and the radius 13 cm.

The complex arm configuration was needed to handle the problem of closed chain dynamics (when holding the ball with both hands). A simpler configuration would be inappropriate, as it would generate infinite contact reactions (forces/torques).

3.2 Analysis of the Results

Figure 15 shows the realized motion of the goalkeeper. His intention (and reference) was to jump, catch the ball with both hands, and land while holding the ball. According to Fig. 5, his attempt was successful. Let us analyze the goalkeeper's motion in more detail. We can observe several phases of the motion:

► ***Phase 1 – takeoff.*** Both legs are in contact with the ground accelerating the body upward (Figs. 5a,b,c). This phase ends at 0.108 *s*. At this instant the legs lose the contact with the ground (Fig. 5c).

● From the viewpoint of mechanics, the flier (goalkeeper in this example) has two contacts with an immobile object – both feet are on the ground. A closed chain is formed. Each contact restricts all six relative motions and, accordingly, creates six reaction forces/torques (twelve reactions in total).

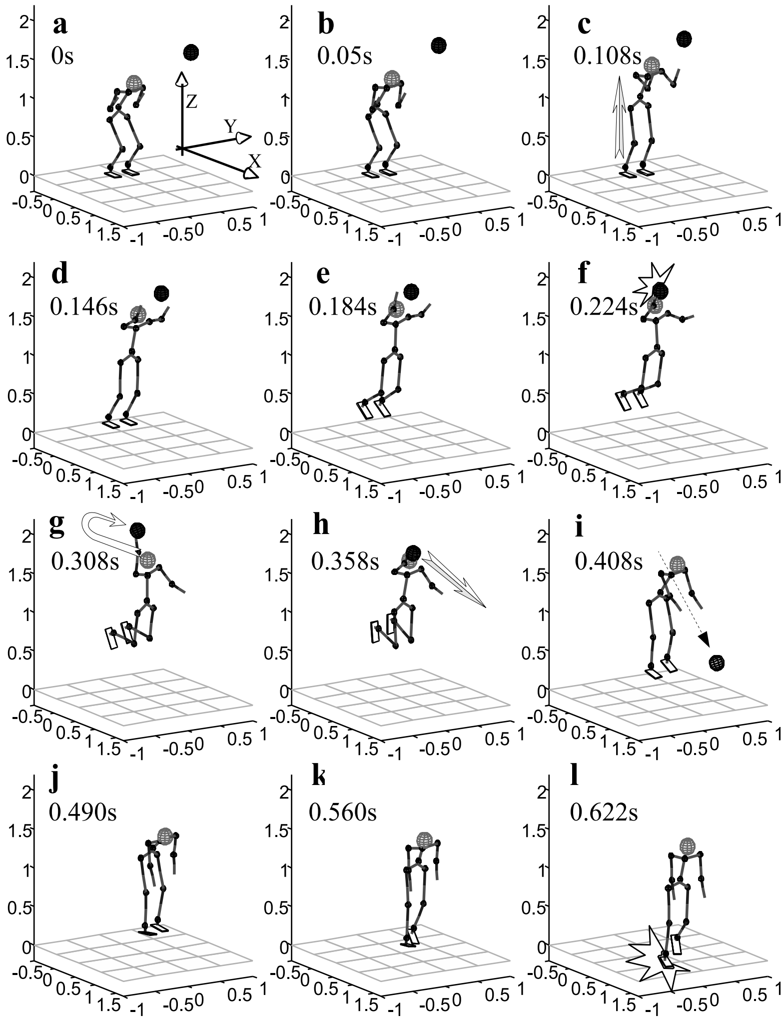

Figure 3
The 'movie' of the human/humanoid player motion. Characteristic instants defining the phases of motion are indicated.

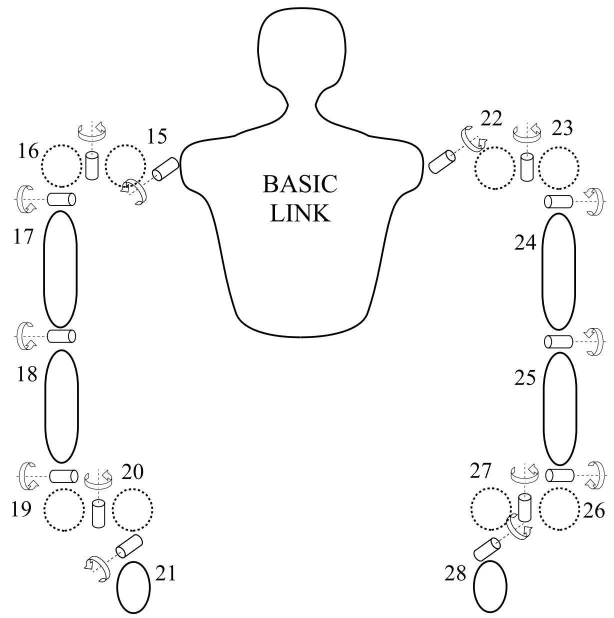

Figure 4
The new configuration of the human/humanoid arms

► ***Phase 2 – free flight towards the ball.*** The goalkeeper is moving (flying) up while expecting the contact with the ball (Figs. 5d, e, f). Both hands establish the contact with the ball simultaneously (catching the ball) at 0.222 *s* and Phase 2 ends (Fig. 5f).

● In this phase, there is no contact with any object; a true flier is considered. The system has a tree structure (no closed chain).

► ***Phase 3 – impact.*** The contact of the goalkeeper's hands and the ball always involve an impact effect. It occurs at 0.222 *s* (Fig. 5f). For the current analysis we assume an infinitely short impact.

● The collision between the motion of the hands and the motion of the object (the ball) will cause an impact. The contact with each hand will restrict all six relative coordinates. So, the complex impact is characterized by one six-component momentum for each hand (twelve components in total). Note that the arms holding the ball form a closed chain. The infinitely short impact will generate infinitely large reactions that will cause instantaneous change in the system velocities.

► ***Phase 4 – falling down.*** The goalkeeper falls down while holding the ball with both hands. In order to guard better the ball, he pulls it towards his waist.

So, the flier has two contacts. The ball and the player now move together (Figs. 5g-l). The contact with the ground is established at 0.66 *s* (Fig. 15 l). The landing is performed correctly, so the goalkeeper will not overturn.

● From the viewpoint of mechanics, two contacts are established between the flier's hands and an external mobile object (the ball). Each contact restricts all six relative motions and produces six reaction forces/torques (twelve reactions in total). The arms holding the ball form a closed chain. The contacted object is a separate system (body) that has its own dynamics, now being influenced by the flier (and vice versa). The entire system is falling down until landing.

Our simulation stops when the player touches the ground.

Conclusion

This paper proposed a general approach to humanoid-robot motion, applicable to any motion task: walking, running, manipulation in industrial environment, gymnastics, basketball, soccer, handball, tennis, etc. It was our idea to promote the method as a tool for biomechanics as well. That is why we used term 'human/humanoid motion', and both examples were selected as sporting motions [11-12].

We are well aware of the extreme complexity of the problem of modeling biological systems, steming from the complexity of the mechanical structure and actuation. Because of that, we started with the dynamic modeling of the structure of humanoid robots, which yielded a solid approximation of dynamics of the mechanical aspect of human motion. The simulation of a truly biological structure is expected as the next step.

By introducing the simple condition of whether contact occurred, that is by introducing prediction when the contact will take place, we gained in the simulation speed. This also yielded a more realistic analysis of sporting tasks of top sportsmen. The prediction when the contact will take place gave more realistic results in the simulation analysis. On the other hand, we are well aware of the fact that in some cases this need not necessarily result in the acceleration of simulation, especially in the situations when two or more players are involved in the game, i.e. when we have the situation of double expectation, which makes the simulation enironment much more complex. However, in such cases the introduction of the appropriate neuro-fuzzy algorithms and advanced planning techniques the proposed solution can yield simulation results corresponding to the real systems.

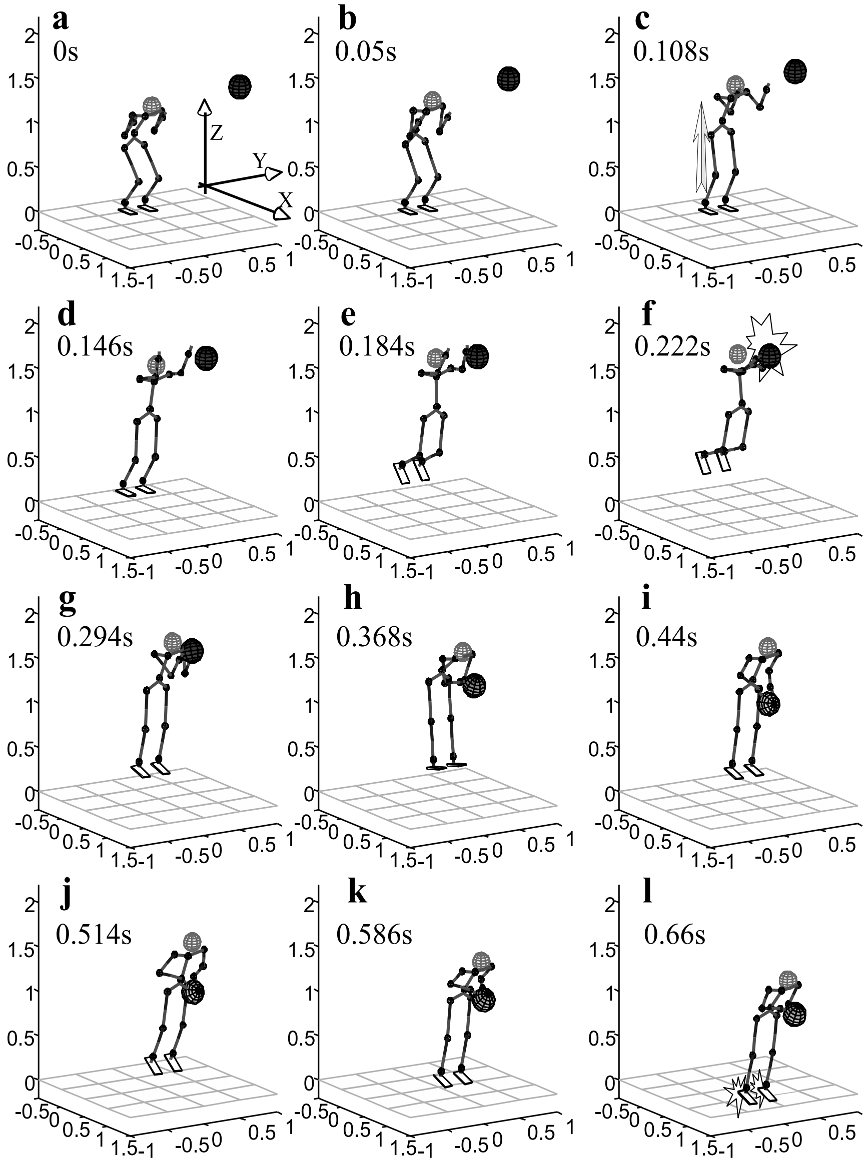

Figure 5

The ‘movie’ of the human/humanoid goalkeeper motion. Characteristic instants defining the phases of motion are indicated.

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