Distributed Compensation and Role of Hands in the Synthesis of Biped Motion with Enhanced Degree of Anthropomorphism

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Abstract: Rapid development of humanoid robots brings about new shifts of the boundaries of Robotics as a scientific and technological discipline. In relation to this, the work raises some new fundamental questions concerning the necessary anthropomorphism of humanoid robots, and how to achieve sufficiently high degree of anthropomorphism with a reasonable number of degrees of freedom. The paper describes a study of the role of hands and two-link trunk in the synthesis of anthropomorphic gait is investigated.

Keywords: humanoid robot, anthropomorphism, zero-moment point, semi-inverse method

1   Introduction

For a long time already, robots have not been present only in industrial plants, at the time their traditional workspace, but have been increasingly more engaged in the close living and working environments of humans. This fact inevitably leads to the need of 'working coexistence' of man and robot and sharing their common working environment. Since no significant rearrangement of the human's environment because of the presence of robots could be expected, robots will have to further 'adapt' to the environment previously dedicated only to man. However, in the time to come it will be inevitable to accept the necessity of cooperative activities of man and robot, and make a step in the direction of increasing comfort of their joint action.

Besides, it is expected that the robots cooperating with humans will have an operation efficiency as close as possible to that of humans. For fulfillment of diverse tasks in the environment highly adapted to humans the most promising is 'human-like' design. Accordingly, the degree of the robot's anthropomorphism may be more concretely conceived as the degree of similarity of its motion and global behavior, whereby the similarity should not be only visual, but some other aspects of anthropomorphism[†] have to be also satisfied.

In this work we will confine ourselves only to considering the anthropomorphism of the artificial bipedal gait. In our previous work [1] we investigated influence of the degree of mechanism complexity to the anthropomorphism. In this work we will focus on influence of distributed compensation and the hands motions on the enhanced of anthropomorphism of synthesized humanoid motion.

2   Gait Synthesis

All of the biped mechanism joints are powered and directly controllable except for the contact of the foot and the ground. The foot can be controlled only in an indirect way – by ensuring the appropriate dynamics of the mechanism above the foot. Thus, the overall indicator of the mechanism behavior is the point where the influence of all the forces acting on the mechanism can be replaced by one single force. This point was termed Zero-Moment Point (ZMP) [2-7].

To realize the motion of a humanoid robot that is as anthropomorphic as possible, it is necessary to synthesize it first under ideal conditions (in the absence of disturbances), which we call reference [8]. Then, such motion should be realized by the real system, so that the deviations from the nominals should be as small as possible, and corrections made in the most anthropomorphic way.

In the realization of artificial walk, the first step is to synthesize the motion that is to be reproduced. Such motion synthesized for the absence of any disturbances is called reference motion. Here we will describe in brief the semi-inverse metod [4,6,9] for the synthesis of the reference motion, a functional and dynamically balanced gait.

The model of system dynamics relates the independent motion coordinates q' and joint drives τ. In the single-support phase, all joint coordinates are independent and hence $q'=q$, while in the double-support phase the number of independent coordinates is reduced due to the contact of the supporting leg with the ground. Depending on the character of contact (heel-strike, flat-foot, etc.) the degree of reduction may vary. In the current discussion we concentrate on the single-support phase without compromising the generality of conclusions. Since $q'=q$, the dynamic model is:

$$\tau = H(q)\ddot{q} + h(q,\dot{q}) + G(q) \tag{3}$$

where **H** is the system inertia matrix, **h** is a vector comprising all 'velocity' influences (Coriolis, centrifugal, etc.), while **G** is a vector of moments due to gravitational forces. The model is used for the synthesis of reference motion and the feed-forward control.

In order to ensure functional movements, the motion for one part of the system should be known in advance. The remaining part of the system should be solved in such a way to maintain the system's dynamic balance for the prescribed boundary conditions (i.e. repeatability conditions). This is why the term 'semi-inverse' method is used. Let us explain this in more detail.

▪ One may assume that the motions of leg joints are prescribed when a desired gait is selected. Let there be n_l such joints: $q^l(t)$. With humans, these are learned walking patterns. Human motions could be recorded and applied to humanoids.

▪ If some manipulation or any other arm activity is to be performed along with walking, then arm joints motions are considered prescribed. Let there be n_a such joints: $q^a(t)$.

▪ The neck has to orient the head in a prescribed direction involving n_n DOFs: $q^n(t)$.

▪ Thus, at $n_l + n_a + n_n$ joints the motion is prescribed. The waist motion is still undefined.

Let there be $n_w = 3$ waist DOFs: q^w. Two of them are utilized to maintain the dynamic balance. These are the trunk rotations left-right and forward-backward. To achieve the balance, these motions are calculated to ensure a desired position of the ZMP inside the support area by applying the two scalar conditions $M_X = M_Y = 0$[1]. The rest waist motion, rotation about the vertical axis, can be either prescribed (if some given task requires it) or can be calculated so as to reduce the friction torque between the foot and the ground. Note that in the situation when the arms are not engaged in any functional activity, they usually move so as to assist the waist in reducing the friction torque under the foot (feet). In this way all $n = n_l + n_a + n_n + n_w$ joint motions (comprising reference motion) can be determined.

Let us discuss somewhat more detailed the role of the hands during the gait. There are three ways in which the hands in relation to the trunk may be treated and, consequently, participate in the process of gait synthesis. They can freely hang on the shoulders as physical pendulums and move only under the influence of inertial

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[1]   It can be also required that Mx = My = Mz = 0 (all three components of the moment at the ZMP).

forces formed during the trunk motion. Further, the hands' joints can be powered and the hands can perform certain motion due to the action of the moments at their own joints, and finally, they can be immobile with respect to the trunk. In the first case, when the hands are freely hanging (passively swinging) as physical pendulums, the hands motion can also be synthesized along with the trunk motion, by prescribing additional conditions at the suspension points at which the moments are naturally equal to zero. In the second case, since their joints are powered, the hands can perform certain predefined motion with respect to the trunk. Therefore, in this case the motions of both the legs and hands are prescribed in advance and compensational motion of the trunk is determined in the process of synthesis in the way to satisfy the conditions of repeatability and dynamic balance. In the third case, when the hands are fixed to the trunk, it can be assumed that they represent its constitutive part, augmenting only the mass and changing thus the inertia moments. Compensational motion of the trunk is calculated in the usual way.

The compensation of each of the ZMP moments (M_X and M_Y) was usualy realized with the aid of only one joint located just below the trunk link. In view of the fact that the compensation of disturbances with humans is performed using several DOFs we have investigated how the gait anthropomorphism is influenced by the distribution of the task of compensation of one moment (M_X or M_Y) on more joints (we call it 'distributed' compensation), whereby the hip DOFs were included in compensation in one case, while the two-link trunk was modeled in the other.

3   Description of the Mechanisms Used in the Work

Structure of the basic mechanism having 39 DOFs, used in the present work, is shown in Fig. 1. The first kinematic chain represents both legs (links 1-27), the second chain extends from the pelvis and comprises the trunk and the right hand (links 28-36) while links 37-39 constitute the left hand. Some of the links correspond to the real mechanism segments (link 9 to the shank, link 12 to the thigh, …), and are presented in Fig. 1 by full lines. However, some links were needed only for the purpose of modeling the joints with more DOFs. Namely, the joints with more DOFs are modeled as sets of more joints having only one DOF each and are connected by the links having mass, moment of inertia and length equal to zero (in Fig. 1 being presented by dashed lines). Thus, for example, the hip joints, being in reality spherical joints with three DOFs, are modeled as a set of three one-DOF joints whose axes are mutually orthogonal. Thus the right hip is modeled by the set of simple joints 13, 14 and 15 (with the unit vectors of rotation axes e_{13}, e_{14} and e_{15}), and the left hip by the set of joints 16, 17 and 18 (unit vectors e_{16}, e_{17} and e_{18}). The links connecting these joints (for the right hip the links 13 and 14, and for the left links 16 and 17 were needed only to satisfy the mathematical formalism of kinematic chain, on which the simulation software is

based) were presented by dashed lines, to indicate their 'fictitious' nature. The other links (those that are not part of the joints with more DOFs) correspond to the real characteristics of the links of an average human body.

The trunk is customarily considered as a single rigid body. However, the trunk's base is the spinal column, which is flexible, so that the assumption on one-link rigid trunk is not quite justified. To investigate the influence of the trunk bending on the performance of the synthesized motion the two-link instead of the one-link trunk was introduced.

The contact of the mechanism with the ground is modeled by two rotational joints, determined with the unit vectors e_1 and e_2 (Fig. 1) mutually perpendicular. At the ZMP, for dynamically balanced motion it is permanently ensured that $M_X = 0$ and $M_Y = 0$ (($M_X \perp M_Y$) $\wedge$ (M_X, $M_Y \in XoY$).
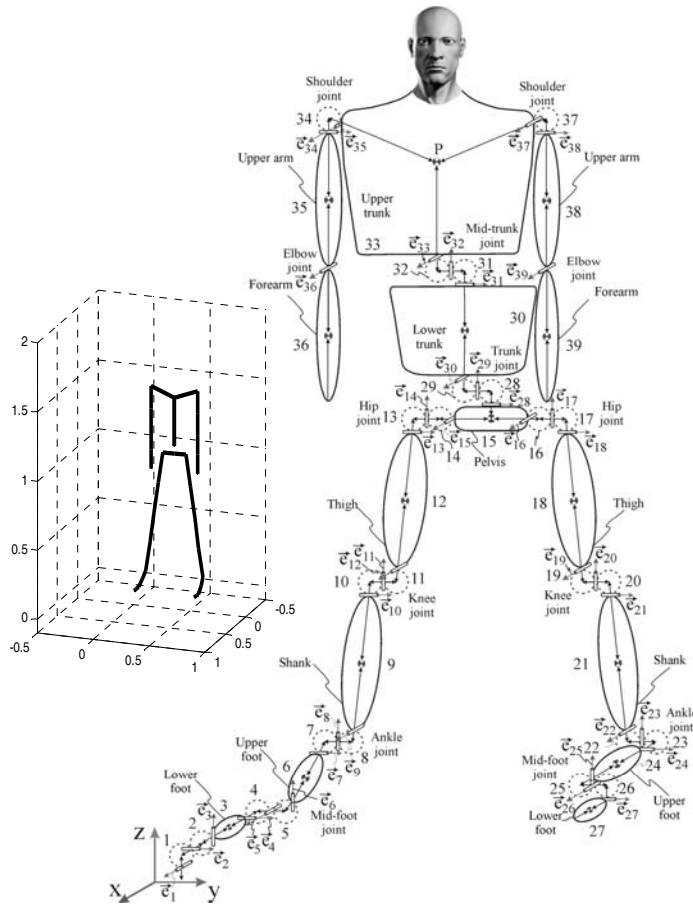

Figure 1

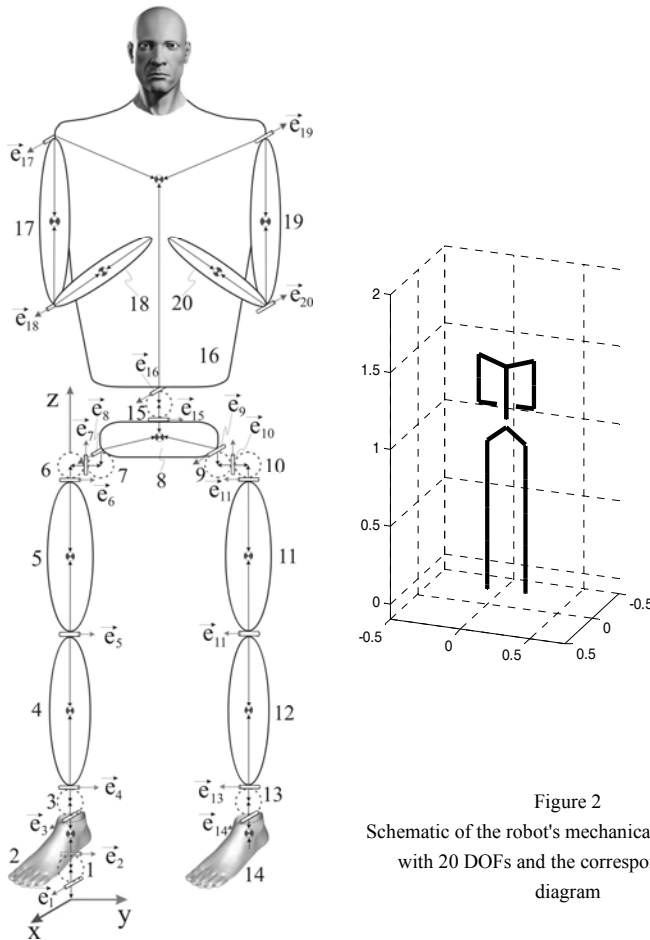Schematics of the mechanical robot configuration having 36 DOFs with the two-link trunk

Figure 2

Schematic of the robot's mechanical configuration
with 20 DOFs and the corresponding stick
diagram

The motion of all the links of the locomotion system was determined on the basis of the semi-inverse method. The basic legs motion pattern was obtained by recording the performance of a human subject, and then, the trunk motion was synthesized in such a way to enable the ground reaction force under the foot is in a certain predefined position, ensuring simultaneously that the horizontal components of ground reaction moment are equal to zero, i.e. $M_x=M_y=0$.

In addition to the mechanism shown in Fig. 1 use was also made of a significantly simpler mechanism with 20 DOFs [6], whose kinematic scheme is presented in Fig. 2. The ZMP is constantly at the origin of the external coordinate frame below the mechanism supporting foot.

In all cases, the synthesis was carried out for one half-step only. The motion in the next half-step was obtained by inverting the motion for the first half-step.
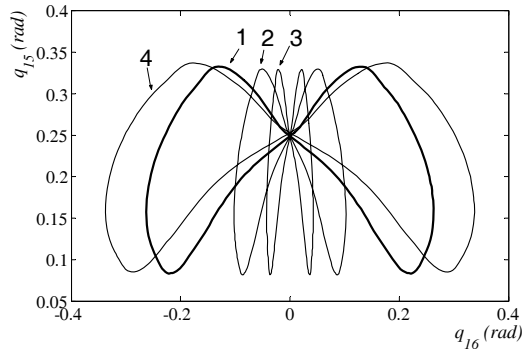
Figure 3
Compensational movements of
the trunk in the case of
distributed compensation with
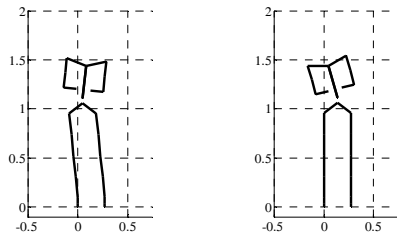the participation of the hips

Figure 4
Stick diagram of the mechanism with
the hips included and not included in
the task of compensation

4   Distributed Compensation

In the 'classical' semi-inverse method the compensational movements of the trunk were synthesized in such a way that the number of moment components under the foot to be compensated equals the number of the used trunk's DOFs for compensation. In the folowing example we will show that the number of DOFs involved in compensation may be larger than the number of compensated moment components.

To make it more obvious, the first example of the synthesis was performed on the model consisting of 20 DOFs. Namely, during nominal motion the legs of this model move in the parallel planes that are perpendicular to the ground and any motion of the hips in the frontal plane is clearly and easily visible.

The reference trunk motion was the one (curve 1 in Fig. 3) obtained by the 'classical' semi-inverse method – the trunk motion in the sagittal plane being realized by joint 15 and in the frontal plane by joint 16.

In the distributed compensation the compensational movements in the sagittal plane are performed again only by joint 15, whereas the compensation in the frontal plane is realized simultaneously by the hip joint (joint 8) and the trunk joint 16, in such a way that the relative ratio of their deviations is given in advance. At
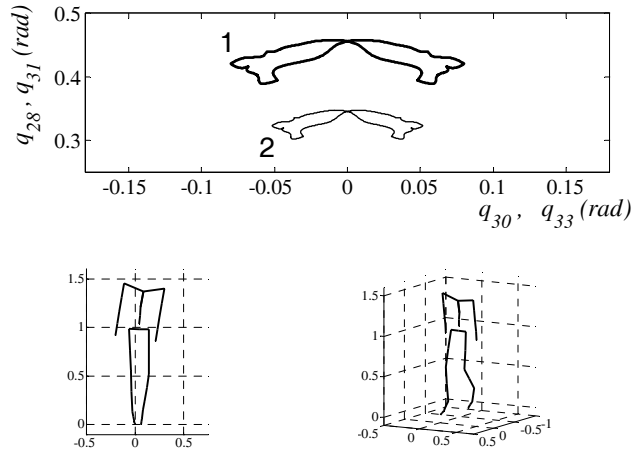
Figure 5
Compensational movements of the trunk for the case
when q30 : q33=1:1, and q28 : q31=1:1

Figure 6
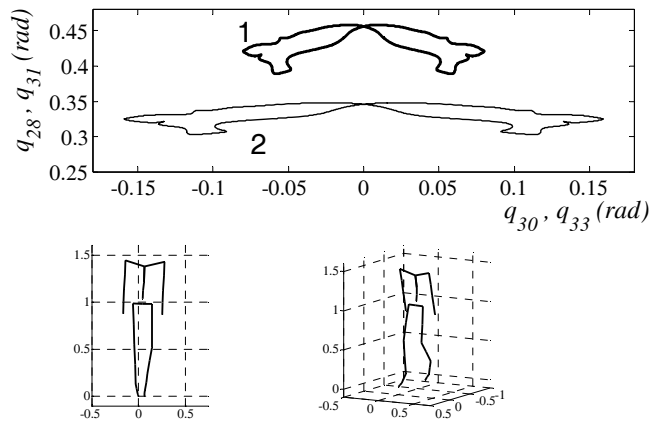Compensational movements of the trunk for the case when q30:
q33=1:-1 in the x-z plane and q28 : q31=1:1 in the y-z plane

that, it should be borne in mind that the legs remain mutually parallel, and the foot is parallel to the ground surface. Hence, depending on the angle at the hip of the supporting leg it is necessary to carry out corrections at other relevant joints of the legs (3, 9 and 14), too. It is possible to vary the (re)distribution of the 'intensity' of compensational movements of the trunk and hip. Curve 2 in Fig. 3 represents the

case when the ratio of the angles realized by joints 16 and 8 is $q^{16}: q^8=1:1$, while curve 3 stands for the ratio $q^{16}: q^8=1:2$ (the hip angle is twice bigger). Curve 4 represents the case when $q^{16}: q^8=2:1$ (the trunk swinging is twice stronger). In Fig. 4 is given the stick diagram of the mechanism for the case without and with the hips engaged in compensation.

In all the above examples the trunk was modeled as one rigid link. Since the human trunk is not rigid but flexible (the base is the spinal column) the first approximation in a technical sense is to divide the trunk into two parts, as presented in Fig. 1. Such a structure of the mechanism is very convenient for distributed compensation, so that the task of compensation is divided between the lower trunk joint (the lower compensational joint) and upper trunk joint (the upper compensational joint). The lower compensational joint consists of joints 28, 29 and 30 and the upper one of joints 31, 32 and 33. Relative ratios of the swinging amplitudes of the lower and upper parts of the trunk in the frontal and sagittal plane can be different. In Fig. 5 is illustrated the case when the trunk inclinations at the lower and upper compensational joint are equal. It should be noticed that the deflections at the two joints (the lower and upper) in the frontal and sagittal plane are the same, and are represented by one curve (curve 2). For illustration sake, we present also the stick diagram of the mechanism at a moment of the walk, showing the posture of the mechanism as a whole.

A whole series of simulation results were obtained for the different ratios of swaying amplitudes at the lower and upper joint, but for the sake of sparing space they will not be presented here.

It is an especially interesting case, and only this will be presented, when the signs of the angles at the lower and upper compensational joints are not the same. Three diferent combinations are possible, and in the example presented in Fig. 6 these ratios are: $q^{30}: q^{33}=1:-1$ (in the frontal plane), and $q^{28}: q^{31}=1:1$ (in the sagittal plane). Stick diagrams illustrate the mechanism postures corresponding to such compensational movements.

5   The Role of Hands in Walking

Hands motion during the walk (swinging) may be either active or passive. In the active movements, which were only considered in this work, moments were applied at the shoulder joints (and potentially at the elbows), whereas in the passive swinging of the hands no moments were present, and the hands moved as physical pendulums (simple or multiple), freely hanging from the shoulders.

We considered three different regimes of swinging imposed on the hands, differing only in the amplitude of hands motion with respect to the trunk, this being 30^0, 60^0, and 120^0. In this case too, the synthesis was performed by the
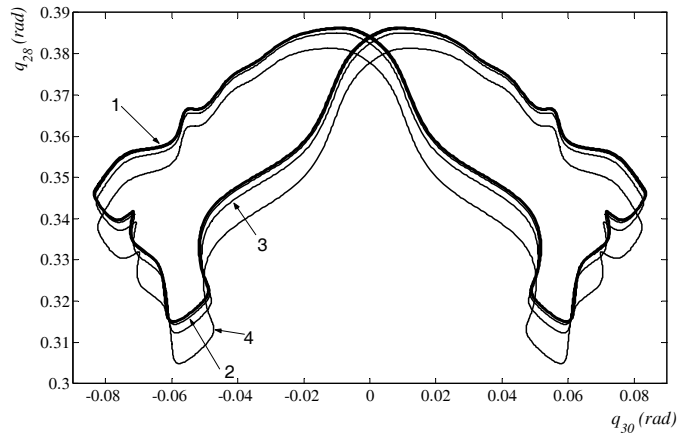
Figure 7

Compensational movements of the trunk in the case of active motion of the hands. Compensation
at the ZMP was carried out only about two axes Mx=My=0.

semi-inverse method. In addition to the motion of the legs, the motion of the hands
(all three regimes) was also prescribed, and the compensational movements of the
trunk were calculated. In Fig. 7, the synthesized movements of the trunk are
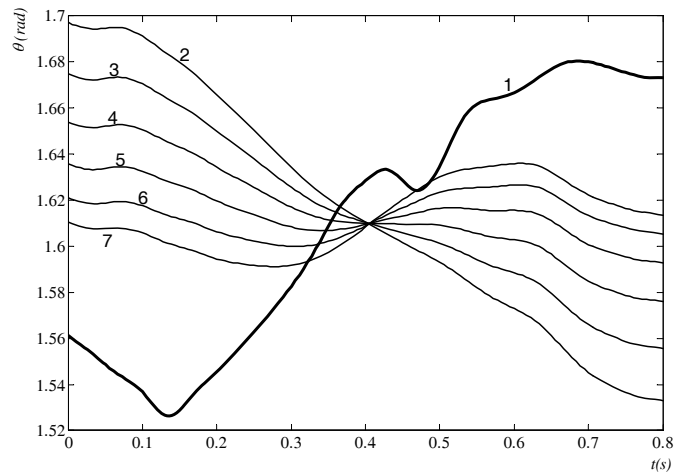shown. Curve 1 represents the trunk motion synthesized in the absence of the

Figure 8

Angle of the trunk rotation with respect to the walking direction

hands motion (reference curve 1), curve 2 (almost coincides with curve 1) shows
the compensational motion when the hands move with a swinging amplitude of
30^0, curve 3 when the amplitude is 60^0, and curve 4 when the amplitude is 120^0. In

the synthesis of compensational movements, in the predefined ZMP position a step, the condition $M_x=M_y=0$ was fulfilled all the time. It is evident that the hands motion does not influence significantly the shape and intensity of the compensational movements, so that a question arises as to the role of the hands during the walk. The situation becomes clearer when, in addition to the mentioned conditions of dynamic equilibrium ($M_x=M_y=0$), a third condition ($M_z=0$) is introduced, namely that the trunk compensates simultaneously for the moment component about the z-axis at ZMP. Results of this synthesis of compensational movements are practically identical to those shown in Fig. 7. This means that the motion of the hands can compensate for the moment M_z and thus reduce the possibility of the foot slippage on the ground and deviation from the walking course. It is also interesting to see how the hands motion influences the intensity of the trunk rotation about its own vertical axis. In Fig. 8 is presented the time change of the angle formed by the line joining both shoulder joints (the centers of links 34 and 37 in Fig. 1) and walk direction (direction of the x-axis). Curve 1 represents the change of the angle in the case when the trunk motion was synthesized under the condition $M_X=M_Y=0$, whereby the hands did not move with respect to the trunk, wheras curve 2 represents the same case but with the addional condition $M_Z=0$ satisfied in the synthesis. Curves 3 - 7 stand for the case when the hands motion was within the amplitudes of 30°, 60°, 90°, 120°, and 150° respectively. It is evident that the introduction of the hands motion reduces the intensity of the trunk rotation (brings curve 2 closer to the horizontal). Therefore, it can be concluded that the active motion of the hands contributes to the annulling the vertical component of the moment at the foot-ground contact, reducing thus the fear of the mechanism's slippage and its deviation from the walking course. The trunk rotation about its vertical axis is also reduced, but only under the condition that the amplitude of active movements of the hands is appropriate. Again we come to the distributed compensation because the fulfillment of the condition $M_Z=0$ is distributed between the hands and the trunk.

Concluding remarks

The expectations to be met by humanoid robots are constantly growing both in number and specificity. Already today we can envisage the ambitious use of service robots in the widest span of activities, from helping (or replacing) humans in hazardous situations and hostile environments to entertainment and 'socializati- on' of man-robot communication. Hence it is necessary to make certain improve- ments and refinements to humanoid robots in the domain of complexity of their mechanisms (DOFs), to ensure their improved performance, which, on the other hand, will demand inclusion of some new, previously neglected, phenomena in their modeling and control.

The anthropomorphism of humanoid robots has certainly much more aspects than considered in this paper, which deals only with the some aspects of gait anthro- pomorphism. However, the dynamically balanced gait being certainly the basic requirement to be met by humanoid robots.

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