Contribution to the Study of 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.

1. INTRODUCTION

Current development of robotics indicates that the spectrum of robotic activities will significantly expand in the near future. Rapid development of humanoid robots brings about new shifts of the boundaries of Robotics as a scientific and technological discipline.

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. The working and living environment, adapted to humans, imposes on robots with their mechanical control structure at least two classes of unavoidable tasks: manipulating various objects from the human environment and motion in a specific environment with the obstacles of the type of staircases, multi-level floors, thresholds, etc. For fulfillment of diverse tasks in the environment highly adapted to humans the most promising is "human-like" design. The first step that would enable robots to realize tasks in the manner and with the efficiency similar to those of humans is to make robot’s structure close to that of humans, i.e. anthropomorphic. 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[1] have to be also satisfied.

In this work we will confine ourselves only to considering the anthropomorphism of the artificial bipedal gait.

In relation to this, the work raises also some new fundamental questions. One of them is surely to which extent "human design" should be "copied", or to which extent robot design ought to be similar to human's? This question could also be formulated in the following, more practical, way: How com-

[1] Activities in the common working and living environment of man and robot imply also some other similarities such as, for example, the interaction and man-robot communication (including also emotional aspects).

plex should be the robot structure (i.e. how many DOFs should robot possess and which they are) in order it would be capable of attaining the desired (high enough) degree of anthropomorphism? Although it is clear that the full mechanical complexity of the human skeleton is practically impossible, and perhaps senseless, to mimic, either from the viewpoint of mechanics or control, it is not á priori known what are the DOFs that predominantly influence the degree of anthropomorphism. Hence, a thought-out and factuality-based answer to this delicate question is needed.

Another question is related to the anthropomorphism of the gait itself that is to be performed by the robotic humanoid mechanism under real conditions. There are two aspects that should be borne in mind. The first is, how to synthesize a gait with the highest possible degree of anthropomorphism, and second, how to preserve the anthropomorphism in the course of gait realization in the presence of disturbances, i.e. how to realize "the most anthropomorphic" compensation of disturbances?

It should also be emphasized that in the control of legged locomotion, and especially that of biped robots, in view of the possibility of occurrence of unpowered (passive) degrees of freedom between the foot and ground caused by larger disturbances, apart from the complete conventional dynamic control (tracking, i.e. maintaining the state of internal coordinates), it is essential to check all the time the fulfillment of the conditions of dynamic balance of the humanoid robot as a whole. In the case of an abrupt compensational movement, however, there may appear such inertial forces that represent a real threat of robot's rotation about the foot edge. Hence, it is necessary to have as natural (moderate) as possible compensation of disturbances, which will bring the robot again to the previous state of dynamic balance.

A fundamental question is how to more precisely define the anthropomorphism of an artificial gait and how to quantify it. Instead of giving a definite answer to this delicate question we will define some relevant attributes of anthropomorphism that are, to our opinion, dominant, so that we will focus our attention on them:

- The amplitudes of particular DOFs of humanoid robots should be kept within the possible moderate range, whereby a decisive influence has the robot's trunk, both in the frontal and sagittal plane. Of course, it is necessary to mention that one can also speak about the relation between the anthropomorphism and compensational motion in the cases of real gait too, when the control mechanism is to solve the problem of maintaining dynamic balance of the humanoid robot in the circumstances of the ever-present disturbances of various types.
- When speaking about the relationship between the magnitude of compensational movements and energy consumption in the cases of forming and maintaining dynamic balance of humanoid robots we should notice that our initial investigations [1] of the model of gait dynamics with the imposed flat-foot contact showed somewhat lower energy consumption in comparison with the "natural" gait, where the foot-ground contact is realized in three phases (heel strike, flat foot and deploy phase). Let us notice that the SONY [2] robot realizes its gait via flat-foot contact with the ground.
- The number of prescribed Zero-Moment Points (ZMP) [3-8] and their distribution within the support polygon, either in the single-support or double-support gait phase, influences the robot's anthropomorphism.
- And the last, but not least important, attribute concerning the functional anthropomorphism of humanoid robots is related to the importance of the choice of mechanical DOFs, such as active segmentation of the foot and trunk, as well as the robot's active rotation about the vertical axis.

The above remarks concerning the anthropomorphism of humanoid robots testify to its significant complexity. The possibility to determine the degree of this integral performance as a solution of the high-complexity optimization problem involving numerous constraints seems to be rather unlikely. Hence we think it more practical to use the approach in which, instead of attempting to find an integral criterion of anthropomorphism, one considers a set of its particular attributes (for example, those mentioned above). Then, taking into account the maximal possible particular attributes of humanoid robots one will arrive at the maximum of its possible overall anthropomorphism, even when it has not been explicitly defined.

In this work, to our knowledge the first one intending to call attention to the problem of anthropomorphism of humanoid robots, we will confine ourselves to the synthesis of the nominal bipedal motion of enhanced degree of anthropomorphism.

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) [3-8].

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 nominal. 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.

For the gait synthesis (defining trajectories of all the mechanism joints) of crucial importance is the semi-inverse method [3-8], in which, upon prescribing the ZMP and trajectories for a part of mechanism joints, trajectories of the remaining joints are calculated and thus the dynamic balance of the overall humanoid robot is ensured. The mechanism motion was synthesized by the semi-inverse method in the following way:

- The legs' motion was copied from a human subject's and adopted as the motion of the mechanism legs;
- The trunk's motion was determined in the way ensuring dynamic equilibrium of the mechanism as a whole during the half-step, i.e. in the period considered, the point within the support polygon that in the given moment represents the ZMP is characterized by the equalities $\mathbf{M}_X = \mathbf{M}_Y = 0$[1];
- Special attention should be paid to 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 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.

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[1] It can be also required that $\mathbf{M}_X = \mathbf{M}_Y = \mathbf{M}_Z = 0$ (all three components of the moment at the ZMP).

The compensation of each of the ZMP moments ($\mathbf{M}_X$ and $\mathbf{M}_Y$) was usually 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 ($\mathbf{M}_X$ or $\mathbf{M}_Y$) 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

The 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 $\mathbf{e}_{13}$, $\mathbf{e}_{14}$ and $\mathbf{e}_{15}$), and the left hip by the set of joints 16, 17 and 18 (unit vectors $\mathbf{e}_{16}$, $\mathbf{e}_{17}$ and $\mathbf{e}_{18}$). 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 $\boldsymbol{e_1}$ and $\boldsymbol{e_2}$ (Fig. 1) mutually perpendicular. At the ZMP, for dynamically balanced motion it is permanently ensured that $\boldsymbol{M_X} = 0$ and $\boldsymbol{M_Y} = 0$ ($(\boldsymbol{M_X} \perp \boldsymbol{M_Y}) \wedge (\boldsymbol{M_X}, \boldsymbol{M_Y} \in XoY)$).

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 per-

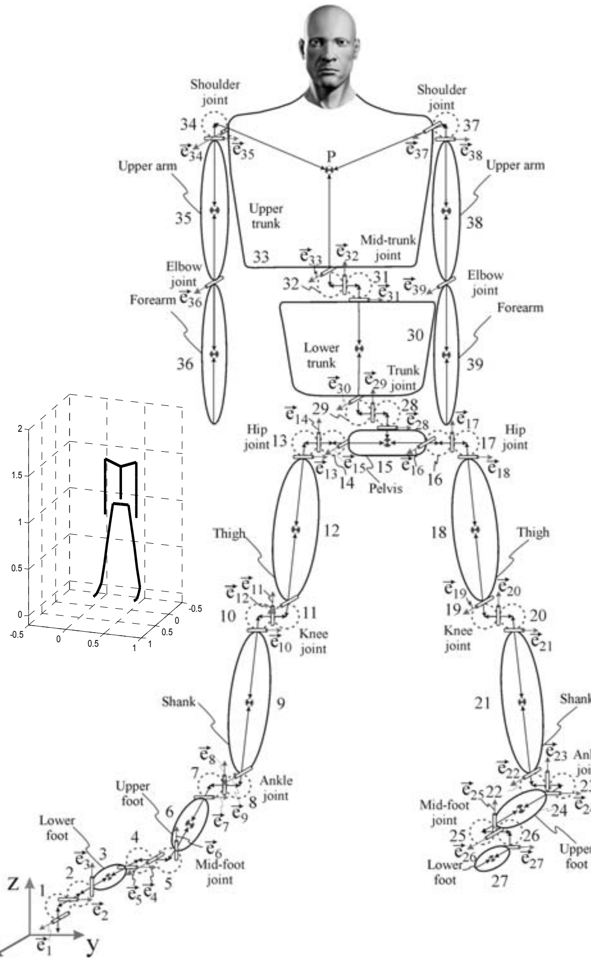
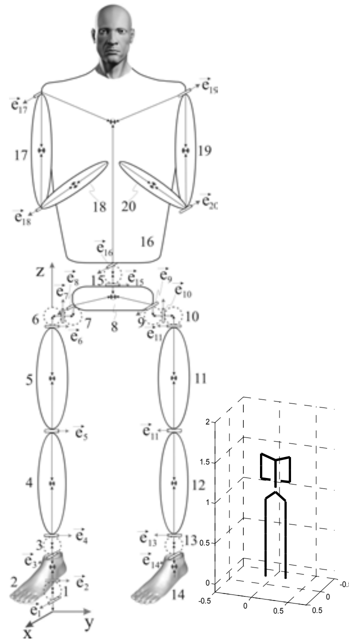


Figure 1. Schematics of the mechanical robot configuration having 36 DOFs with the two-link trunk



a.) kinematic scheme **b.)** stick diagram

Figure 2. Schematic of the robot's mechanical configuration with 20 DOFs and the corresponding stick diagram

formance 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. $\mathbf{M}_X=\mathbf{M}_Y=0$.

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 legs of this mechanism move in the planes that are parallel to each other as well as to the *x*-axis of the external coordinate frame, and at the same time are perpendicular to the plane of the ground on which the mechanism walks. The ZMP is constantly at the same place – 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 synthesized for the first half-step.

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 used trunk's DOFs for compensation. In the following 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 that, it should be borne in mind that the legs remain mutually parallel, and the

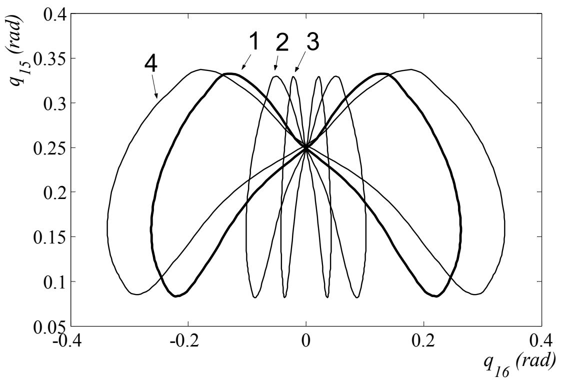


Figure 3. Compensational movements of the trunk in the case of distributed compensation with the participation of the hips

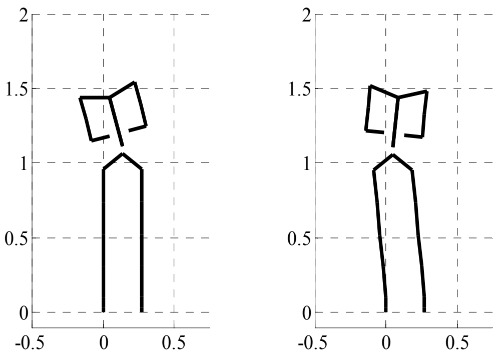


Figure 4. Stick diagram of the mechanism with the hips not included (a) and included (b) in the task of compensation

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 (a) and with (b) 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 different 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.

4. THE ROLE OF HANDS IN WALKING

Hands motion during the walk 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 motion 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 motion imposed on the hands, differing only in the amplitude of hands motion with respect to the trunk, this being 30º, 60º, and 120º.

In this case too, the synthesis was performed by the semi-inverse method. In addition to the mo-

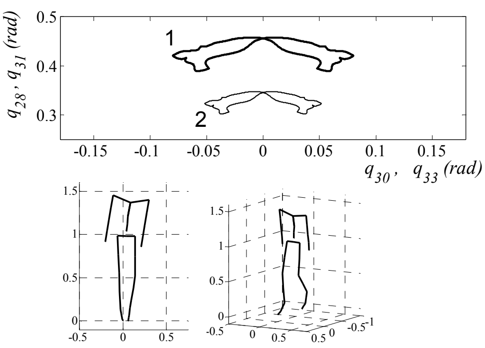


Figure 5. Compensational movements of the trunk for the case when q^{30} : q^{33}=1:1, and q^{28} : q^{31}=1:1

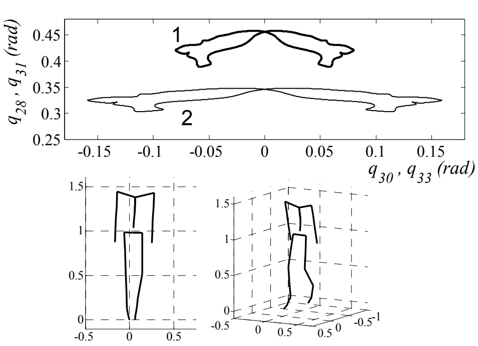


Figure 6. Compensational movements of the trunk for the case when q^{30} : q^{33}=1:-1 in the x-z plane and q^{28} : q^{31}=1:1 in the y-z plane

tion 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 hands motion (reference curve 1), curve 2 (almost coincides with

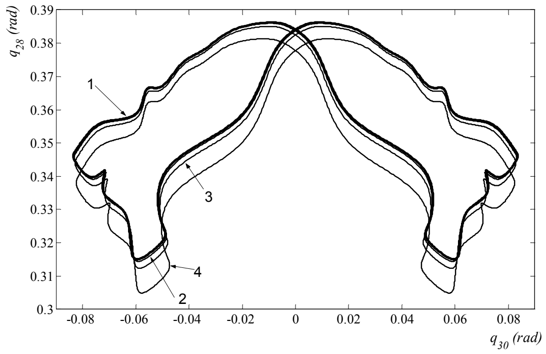


Figure 7. Compensational movements of the trunk in the case of active motion of the hands. Compensation at the ZMP was carried out only about two axes Mx=My=0.

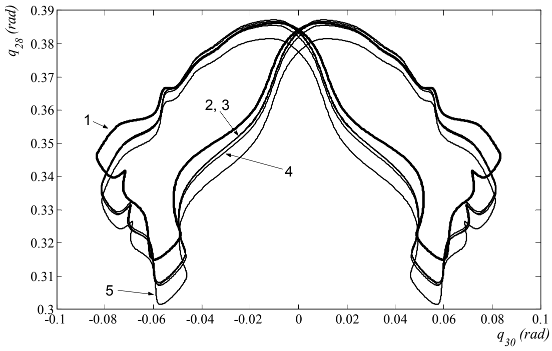


Figure 8. Compensational movements of the trunk in the case of active motion of the hands. Compensation at the ZMP was carried out for all three axes, i.e. $\boldsymbol{M_x}$=$\boldsymbol{M_y}$=$\boldsymbol{M_z}$=0.

curve 1) shows the compensational motion when the hands move with a swinging amplitude of 30º, curve 3 when the amplitude is 60º, and curve 4 when the amplitude is 120º. In the synthesis of compensational movements, in the predefined ZMP position during a step, the condition $\mathbf{M}_X$=$\mathbf{M}_Y$=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 ($\mathbf{M}_X$=$\mathbf{M}_Y$=0), a third condition ($\mathbf{M}_Z$=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, shown in Fig. 8, are practically identical to those shown in Fig. 7. This means that the motion of the hands can compensate for the moment $\mathbf{M}_Z$ 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. 9 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 $\mathbf{M}_X$=$\mathbf{M}_Y$=0, whereby the hands did not move with respect to the trunk, whereas curve 2 represents the same case but with the additional condition $\mathbf{M}_Z$=0 satisfied in the synthesis. Curves 3 - 7 stand for the case when the hands motion was within the amplitudes of 30º, 60º, 90º, 120º, and 150º 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 ap-

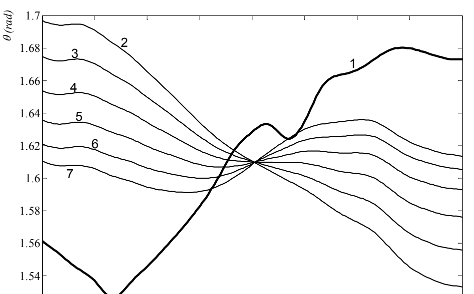


Figure 9. Angle of the trunk rotation with respect to the walking direction

propriate. Again we come to the distributed compensation because the fulfillment of the condition $\mathbf{M}_Z=0$ is distributed between the hands and the trunk.

5. 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 "socialization" of man-robot communication. Hence it is necessary to make certain improvements 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 problem of gait anthropomorphism. However, to our knowledge, this is the first attempt to treat the anthropomorphism of humanoid robots in a systematic way, the dynamically balanced gait being certainly the basic requirement to be met by humanoid robots.

Authors are well aware of the fact that it is not possible to present a sufficiently general view of this extremely important issue in the frame of one paper, so that an all-rounded result is naturally missing, primarily because of technical limitations. However, we hope that we succeeded in giving a sufficiently founded initial result in this extremely important attempt to expand the area of humanoid robotics to cover some new tasks of modeling, dynamic analysis, and control of any human-like motions, from those involved in household duties, via the industrial jobs, to sports and beyond. We wanted, and hopefully succeeded, to point out to all the complexity of this problem, which requires urgent steps in its further systematic treatment.

ACKNOWLEDGEMENT

This work was supported by the Ministry of Technology and Development of Republic of Serbia under contract MIS 3.04.0019.A/1. Data used for legs reference trajectories was obtained from mocap.cs.cmu.edu. The database was created with funding from NSF ELA 0196217.

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