Contribution to the Integrated Control of Artificial Human Gait

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Abstract: The work is concerned with the integrated dynamic control of humanoid locomotion mechanisms based on the spatial dynamic model of humanoid mechanism, model of the servo-system and environment model. The control scheme was synthesized using the centralized model and the hierarchical principle, with two control levels – tactical and executive. The proposed structure of dynamic controller involves four feedback loops: position-velocity feedback of the robotic mechanism joints, dynamic reaction feedback around Zero-Moment Point, contact force feedback at the moment of the foot striking the ground and the load feedback at the mechanism joints. Simulation experiment was carried out for a characteristic example. On the basis of numerical results critical evaluation of the devised controller was carried out and the corresponding conclusions were derived.

Keywards: Humanoid robots; biped locomotion; dynamically balanced gait; integrated dynamic control.

1 Introduction

Studies in the area of humanoid robotics have recently made a remarkable progress, especially during the last decade. Suffices it to mention only a few of humanoid robots that have attracted great attention of professional community. Apart from such robots from HONDA family that are ready to replace humans in diverse situations, the light of day have recently seen their descendant ASIMO, dedicated primarly to imitation and entertainment. The mobility of ASIMO and its speed of movement give it the possibility of play skills, whereby the Zero-Moment Point (ZMP) is capable to meet its very strong challanges. One of the latest novelties in humanoid robotics is the SONY robot, which wins over people with its unbelievable mobility. At the present it is an 'entertainer' but it may happen soon that some of its versions will be in charge of much more serious business, or even dangerous jobs. While presenting some of the most attractive humanoids the authors of this paper are faced with the appearance of several magnificent creations of human's counterparts, from which on this occasion we point out only these: PINO robot produced in ZMP Inc., Tokyo, HRP-2 manufactured by Kawada Industries, H-6 realized at Tokyo University, MONROE robot realized at Tohoku University, SAIKA-3 also from Tohoku University, and

KHR-1 produced at the Korea Advanced Institute of Science and Technology. It should be emphasized that more than ten humanoid projects are currently in progress worldwide, so that in the near future the number of representative humanoids will grow up. Having in mind very high requirements to be satisfied by humanoid robots it should be pointed out the need to increase the number of degrees of freedom (DOFs) of their mechanical configuration, to study in more depth some previously unconsidered phemomena in the stage of forming the corresponding dynamic models of humanoids, as well as the need to make appropriate controller software that would be capable of meeting the most complex requirements of stable trajectory tracking and maintaining dynamic balance of both the regular (stationary) gait in the presence of small perturbations and of the robot posture in the case of large perturbations. It should be also pointed out that the problem of motion of humanoid robots is a very complex control task, especially when the real environment (scene) is taken into account, which, as minimum, requires its integration with the robot's dynamic model.

The scope of our interests in this paper is to deal with the two lower control levels: the tactical level (which performs the distribution of elementary movements to the motion of each DOF) and the executive level (which executes the imposed motion of each DOF). In that sense, a novel, integrated dynamic control structure for the humanoid robots is proposed, using the overall model of robot mechanism and its interaction with dynamic environment.

2 System Modeling

2.1 Model of the Robot's Mechanism

Biped locomotion mechanisms represent generally branched kinematic chains interconnected with spherical or cylindrical joints [1]. During the motion, some kinematic chains in their interaction with the environment transform from open to closed type of chain [2]. In Fig. 1 is shown the kinematic scheme of the biped locomotion mechanism [1] whose spatial model will be considered in this work. The model will be used to synthesize dynamic control of the locomotion mechanism and to verify the research results obtained in simulation experiments. The mechanism possesses 18 powered DOFs, designated by the numbers *1-18*, and two unpowered DOFs (*1'* and *2'*) for the footpad rotation about the axes passing through the instantaneous ZMP position. Thus, the considered mechanism has in total *n=20* DOFs of motion. By its complexity, the chosen model satisfies the requirements and needs of research in the domain of synthesizing dynamic control of spatial motion of the locomotion mechanism of anthropomorphic structure [1].

The mechanism dynamic model presented in Fig. 1 has been formed using the relations known from Newton's rigid body dynamics.
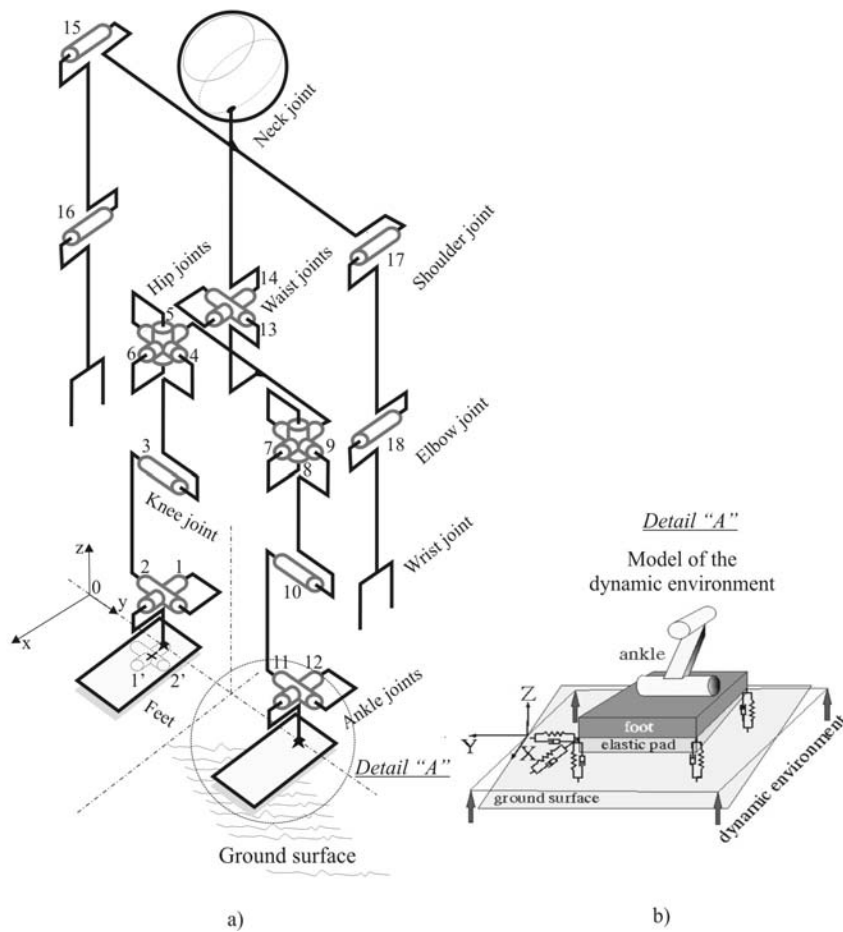
Fig. 1. Model of the humanoid locomotion mechanism with 18 active and 2 passive DOFs [1]: (a) kinematic scheme of the mechanism, (b) dynamic model of the environment

3 Control Synthesis

Human walk represents one of the most complex motions. For its realization, in the complete skeletal activity of human being, there are at the disposal more than 650 muscles [1]. If, by a certain approximation, this number is transformed into an equivalent driving mechanism it would correspond to more than 300 equivalent mechanical DOFs. Hence, depending on their dedication, humanoid

robots ought to have a sufficient number of DOFs, to allow its functionality by simultaneous control of a large number of DOFs.

3.1 Definition of Control Criteria

In the synthesis of control for biped mechanism gait it is necessary to satisfy certain natural principles. The control ought to satisfy the following criteria: (i) accuracy of tracking the desired trajectories at the mechanism joints (ii) maintaining dynamic balance of the mechanism during the motion, (iii) minimization of the impact arising at the moment of contact of the free foot and the ground during the gait, (iv) minimization of dynamic loads at the robot joints, and (v) realization of anthropomorphic characteristics of the gait.

Fulfillment of criterion (i) enables realization of the desired mode of motion, walk repeatability and avoiding of potential obstacles in the way. To satisfy criterion (ii) it means to have a stable balanced walk. Fulfillment of criterion (iii) ensures a higher degree of stability of the overall system in respect of the impact appearing at the moment when the unconstrained leg foot strikes the ground. Fulfillment of criterion (iv) is needed for the purpose of minimizing dynamic loads at the robotic joints, which is especially important for the joints bearing the highest load during the walk, e.g. the hip. Criterion (v) is related to the quality of walk realization. Walk of a physically healthy human represents a balanced and harmonious sequence of movements, with minimal dislocations of the position of its mass center about an imaginary central position corresponding to human's posture at rest.

3.2 Gait Phases and Indicator of Dynamic Balance

The robot's bipedal gait consists of several phases that are periodically repeated [1,3]. At that, depending on whether the system is supported on one or two legs, two macro-phases can be distinguished, viz.: (i) single-support phase (SSP) and (ii) double-support phase (DSP). Double-support phase has two micro-phases: (i) weight acceptance phase (WAP) or heel strike, and (ii) weight support phase (WSP). Fig. 2 illustrates these gait phases of biped robot locomotion, with the projections of the contours of the right (RF) and left (LF) robot foot on the ground surface, whereby the shaded areas represent the zones of the direct contact with the support. While walking, the biped is constantly in the state of a certain dynamic balance. The indicator of the degree of dynamic balance is the ZMP, i.e. its relative position with respect to the footprint of the supporting foot of the locomotion mechanism. The ZMP is defined [4,5] as the specific point under the robotic mechanism foot at which the effect of all the forces acting on the mechanism chain can be replaced by a unique force, and at which all the rotation moments about the x and y axes are equal to zero.
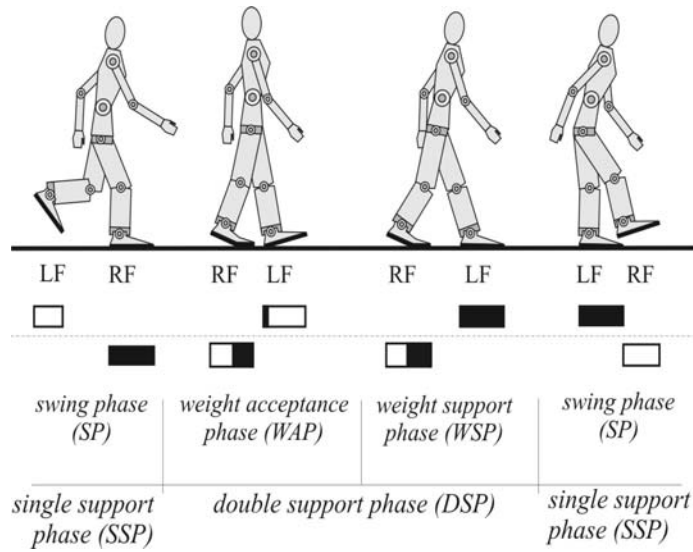
Fig. 2. Phases of biped gait

In Figs 3a and 3b are illustrated details related to the determination of the ZMP position and its motion in the case of a dynamically balanced gait.
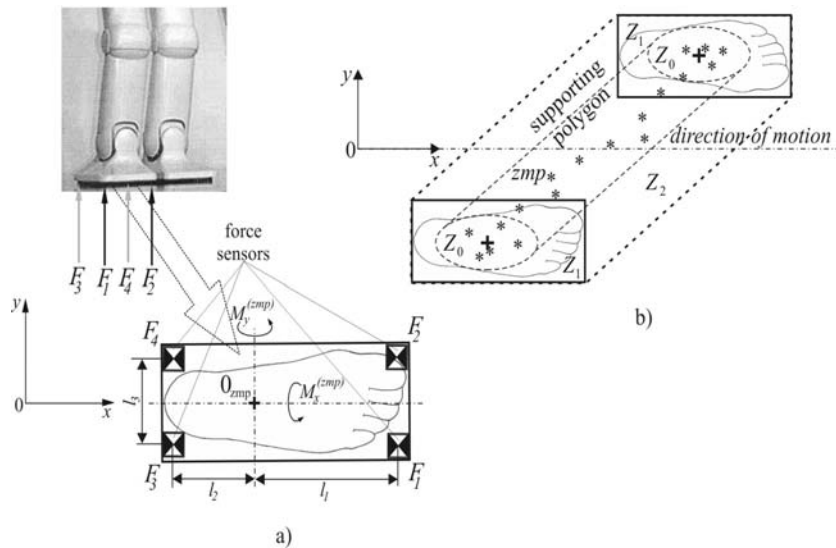

Fig. 3. Zero-Moment Point: a) Legs of "Toyota" humanoid robot [6]; General arrangement of force sensors in determining the ZMP position; b) Zones of possible positions of ZMP when the robot is in the state of dynamic balance

The ZMP position is determined by the calculation based on measuring reaction forces under the robot foot. Force sensors are usually placed on the foot sole in the arrangement shown in Fig. 3a. Positions of the sensors are determined by the geometric quantities l_1, l_2 and l_3. If the point 0_{zmp} is taken as the nominal position of the ZMP, then we can write the following equations:

$$\frac{l_3}{2}\left[(F_2+F_4)-(F_2^0+F_4^0)\right]-\frac{l_3}{2}\left[(F_1+F_3)-(F_1^0+F_3^0)\right]= M_x^{(zmp)} =$$
$$= F_r^{(z)}\cdot\Delta y^{(zmp)},$$
$$l_2\left[(F_3+F_4)-(F_3^0+F_4^0)\right]-l_1\left[(F_1+F_2)-(F_1^0+F_2^0)\right]= M_y^{(zmp)} = \tag{1}$$
$$= F_r^{(z)}\cdot\Delta x^{(zmp)}.$$

where F_i and F_i^0, $i=1,\ldots,4$, are the measured and nominal values of the ground reaction force; $F_r^{(z)}$ is the resultant force of ground reaction in the vertical z-direction, while $\Delta x^{(zmp)}$ and $\Delta y^{(zmp)}$ are the displacements of ZMP position from its nominal 0_{zmp}. The deviation of the ZMP from its nominal position is calculated from the relation (5). Instantaneous position of the ZMP is the best indicator of the dynamic balance of the biped robot. In Fig. 3b are illustrated certain areas, the so-called *zones of dynamic balance* of the locomotion mechanism. These are: Z_0, Z_1 and Z_2. The ZMP position inside these stability areas ensures dynamically balanced gait of the mechanism [3], whereas its position outside these zones indicates the state of instability of the overall mechanism and the possibility of its overturning, i.e. colapse. The quality of controling the robot balance can be measured by the success in tracking the ZMP trajectory within the support polygon of the mechanism (Fig. 3b).

3.3 Control Design

Biped locomotion mechanism represents a nonlinear multivariable system with several inputs and several outputs. Bearing in mind the control criteria from Section 3.1, it is necessary to control the following quantitites: positions and velocities of the robot joints, the ZMP position [1,7], contact force at the moment foot striking the ground, i.e. at the moment of weight acceptance by the other leg, and dynamic load forces at the particular joints of the mechanism. In accordance with the control task, we propose the application of the algorithm of the so-called integrated dynamic control, based on the knowing of the overall dynamic model of the system (1)-(3). At that, it is assumed that the following assumptions hold: (i) the model (1)-(3) describes sufficiently well the behavior of the system presented in Fig. 1; (ii) Desired (nominal) trajectory of the mechanism performing a

dynamically balanced gait is known during motion. It is determined off-line (by some of the known mathematical methods) or calculated in real time on some of higher robot control levels; (iii) Geometric and dynamic parameters of the mechanism and driving units are known and constant. These assumptions can be taken as conditionally valid, the rationale being as follows: Parameters of the mechanism and actutors can be determined with a satisfactory accuracy as the system elements are rigid bodies of unchangeable geometrical shapes. The Coulomb friction at joints and backlashes in the gearings can be neglected with contemporary driving units with which these phenomena are reduced to a minimum.

Based on the above assumptions, in Fig. 4 is presented the block-diagram of the dynamic controller for biped locomotion mechanism, proposed in this work. It involves four feedback loops: (i) position-velocity feedback [8], (ii) dynamic reaction feedback at the ZMP, (iii) contact-force feedback [8] on the foot of the unconstrained leg, and (iv) load feedback at the mechanism joints. The dynamic controller presented in Fig. 4 has two control levels: tactical and executive. Structurally, the controller consists of the so-called 'Basic dynamic controller' (Trajectory tracking controller + Compensator of dynamic reactions, Fig. 4) and two additional load compensators that are activated by the switches K_1 and K_2, according to the need and depending on the preset control task. The synthesized dynamic controller (Fig. 4) was designed on the basis of the centralized model and the hierarchical principle, using the overall dynamic model of the mechanism and model of the servo-system. The actuators driving moments $\hat{P}$ at active robot joints (1 to 18 in Fig. 1), needed to realize the desired motion of the locomotion mechanism as well as to perform additional compensation actions, are calculated on the tactical control level. The vector of driving moments $\hat{P} \in R^{n \times 1}$ represents the sum of the driving moments $\hat{P}_1$, $\hat{P}_2$, $\hat{P}_3$ and $\hat{P}_4$. The moments $\hat{P}_1$ are determined so to ensure precise tracking of the robot's position and velocity in the space of joints coordinates. The driving moments $\hat{P}_2$ are calculated with the aim of correcting the current ZMP position with respect to its nominal. The moments $\hat{P}_3$ are determined with the aim of diminishing the amplitude of the force F that arises at the moment of contact of the free foot and the ground. The moments $\hat{P}_4$ are calculated for the purpose of reducing dynamic loads at the particular robot joints. The vector of driving moments $\hat{P}$ represents the output vector of the control signals of the tactical control level. It serves as the input, reference signal on the executive control level. The current values of positions $q(t)$, velocities $\dot{q}(t)$ and accelerations $\ddot{q}(t)$ of the locomotion mechanism joints, using the servo-system model (3), serve as the basis for calculating the vector of control voltage u of the actuators (Fig. 4). The control voltages are transmitted to the output device of the controller and then to the driving units (actuators).
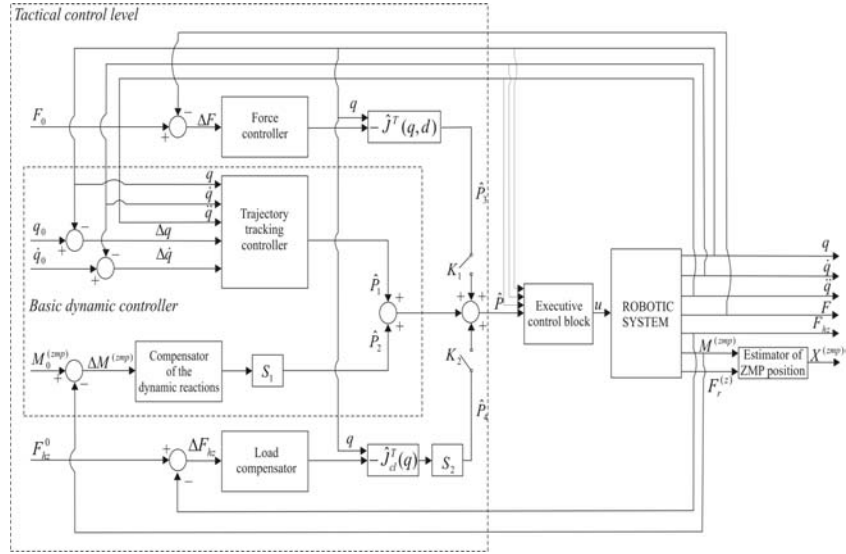
Fig. 4. Block-scheme of the integrated dynamic control of biped locomotion
mechanism with four feedback loops in its structure and with the executive control
block as the lowest control level

4 Simulation Experiments

Theoretical results presented in Section 3 were analyzed on the basis of
numerical data obtained by simulation of the closed-loop model of the locomotion
mechanism shown in Fig. 1. Total mass of the mechanism was $m = 70 \, [kg]$ and
its geometric and dynamic parameters were taken from [1]. Simulation examples
are concerned with the characteristic pattern of artificial gait in which the
mechanism makes a half-step of the length $l = 0.40 \, [m]$ in the time period of
$t = 0.75 \, [s]$. The half-step is repeated with this period, whereby the gait phases
presented in Fig. 2 alternate regularly. Nominal trajectories at robot joints are
synthesized for the gait in the horizontal plane. Nominal angles at the mechanism
joints and the corresponding angular velocities and accelerations are determined
by the semi-inverse method [1]. The simulation results were analyzed on the time
interval corresponding to the duration of one half-step of the locomotion
mechanism in the swing phase (Fig. 2). In the analysis of the efficiency of the
developed dynamic controller (Fig. 4) in realizing dynamically balanced motion
the most delicate is the single-support phase (swing phase), as well as the moment
when the so-called free foot touches/strikes the ground. For this reason of special

importance for control is the analysis of dynamic robot behavior in these time intervals, so that the simulation examples were selected to encompass these critical phases.

In the first simulation example the assigned initial deviations of particular angles at mechanism joints did not exceed $\Delta q_i \leq 10°$. Constant inclinations of the ground surface in the sagittal plane $\gamma_1 = 3°$ and frontal plane $\gamma_2 = 2°$ were introduced as an additional disturbance [9]. Thus the simulation dealt with the real case of walking on a quasi-horizontal support. Of concern was the robot's behavior in the swing phase (Fig. 2) when the robot by its rigid foot relies on the ground while the other (free) foot is above the ground surface. At that, two cases of control were analyzed: (i) applying only the controller of tracking the given trajectory with position-velocity feedback (Fig. 4) and (ii) applying the combined control with the controller of trajectory tracking and compensator of dynamic reactions of the ground around the ZMP. In the case (ii) use was made of the control structure called 'Basic dynamic controller' (see Fig. 4).

In Fig. 5 are presented the comparative results of applying the controller in cases (i) and (ii). On analyzing the results presented in Figs. 5a and 5b one can see that the ZMP positions in case (i) are concentrated at the corner of the projection of the supporting leg (support polygon), and even outside it, whereas in case (ii) they are mainly within the 'safety zone' Z_0 (Fig. 2). Thus, it can be concluded that without the feedback with respect to the ground reactions around the ZMP it is not generally possible to ensure dynamic balance of the locomotion mechanism in its motion. This comes out from the fact that the nominal trajectory was synthesized without taking into account the possible deviations of the surface on which biped walks from an ideally horizontal plane. Therefore, the ground surface inclination influences the system's balance as an external stochastic disturbance. In Fig. 6 are presented the corresponding deviations (errors) Δq_i and $\Delta \dot{q}_i$ of the real values of angles and angular velocities at the robot joints from their nominal values when the controller of tracking desired trajectory was applied. The deviations of the variables converge to a zero value on the given time interval, which means that the controller employed ensured good tracking of the desired trajectory. In Fig. 7 are presented the corresponding control moments at the robot joints $\hat{P}_1$ and $\hat{P}_2$ (Fig. 4), whose application ensures a stable behavior of the locomotion mechanism illustrated in Figs. 5b and 6. Simulation results shown in Figs. 5 and 6 confirm the efficiency of the application of the proposed basic dynamic controller in the robot's gait on the supporting surface whose inclination angle deviates from the ideal horizontal plane up to $\gamma_1 (\gamma_2) \leq 10°$.

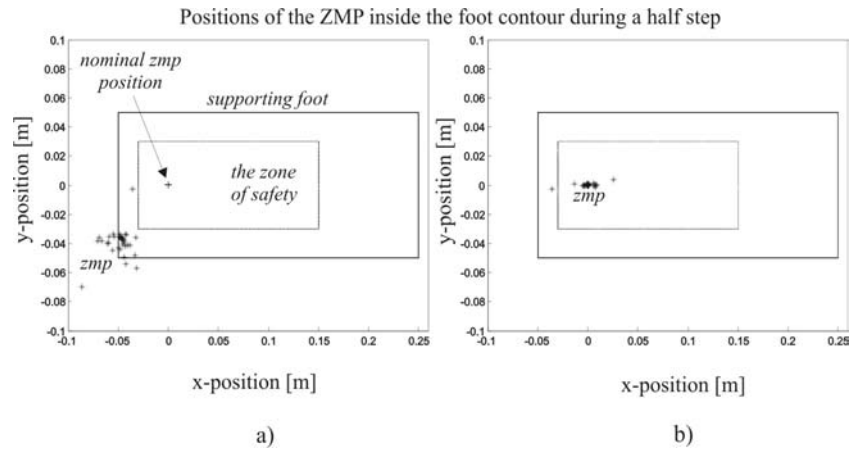Positions of the ZMP inside the foot contour during a half step

a)

b)

Fig. 5. Position of the ZMP in the swing phase of the robot's gait on an inclined surface in the case of applying: a) Trajectory-tracking controller and b) Combined trajectory-tracking controller and compensator of dynamic reactions of the ground around the ZMP

Position errors of biped joints

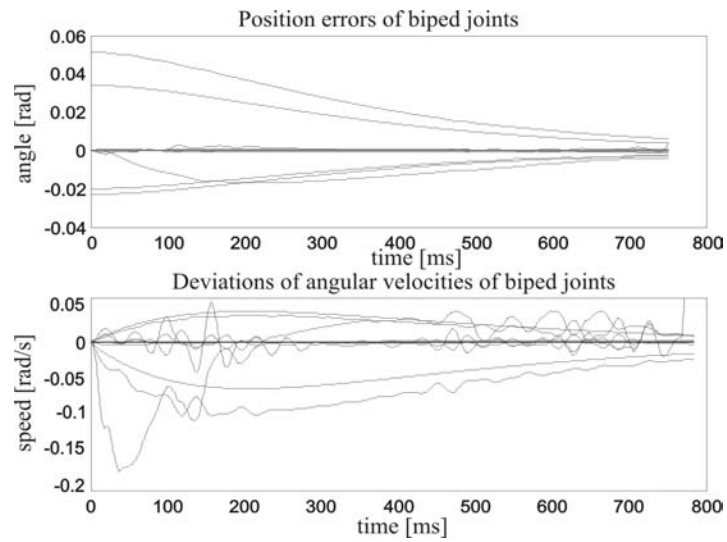Deviations of angular velocities of biped joints

Fig. 6. Convergence of the errors of tracking nominal angles and angular velocities at the robot's joints by applying the control scheme from Fig. 4
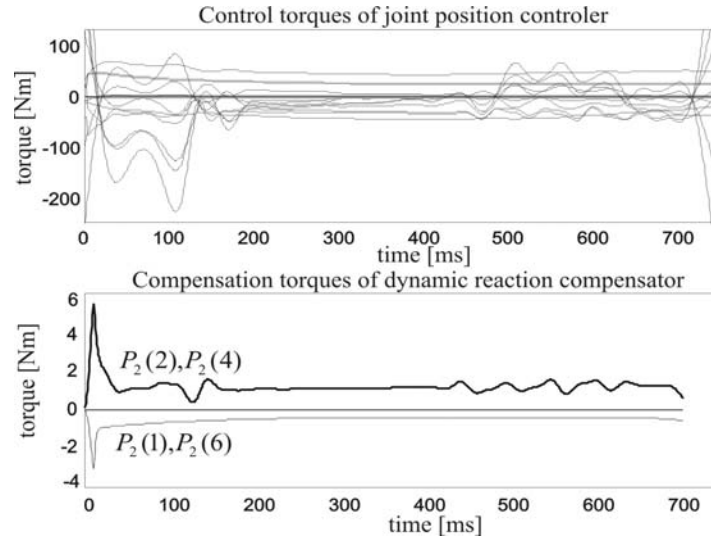
Fig. 7. Control moments $\hat{P}_1$ and $\hat{P}_2$ at the mechanism joints (Fig. 1) that ensure precision of tracking the given robot trajectory and dynamic balance during the mechanism's gait

5 Concluding Remarks

The control scheme of an integrated dynamic controller of locomotion mechanism was synthesized. The proposed scheme was designed by using the centralized model and the hierarchical structure having two control levels – tactical and executive. At the tactical control level, the so-callled 'basic dynamic controller' was synthesized, consisting of a dynamic controller for tracking robot's nominal trajectory and a compensator of dynamic reactions of the ground around the ZMP. At that, feedback loops were formed with respect to position and velocity of the mechanism joints, as well as with respect to dynamic ground reactions. Basic dynamic controller was designed with the aim of ensuring precise tracking of the given motion and maintaining dynamic balance of the humanoid mechanism. The primary control structure was supplemented with two additional feedback loops involving ground reaction force and loads at particular mechanism joints. The function of the contact-force controller and joint-load compensator is to stabilize the forces and loads around the nominal values that were determined for the nominal conditions of motion.

At the executive control level, the applied feedback loops involve the robot's positions, velocities and accelerations of joints. Also, the driving moments calculated at the tactical control level (the dynamic controller output) serve as

input signals. The output signals of the executive control level represent the calculated control voltages at the rotors of the actuators.

The proposed control scheme (Fig. 4) fulfills the preset control criteria defined in Section 3.1. Its application ensures the desired precision of robot's motion, motion stability in the sense of maintaining dynamic balance of the locomotion mechanism, and minimization of the impulse action of load forces at the joints, as well as of the forces due to foot striking the ground during the motion.

The developed integrated dynamic controller exhibits robustness against parametric and structural uncertainties of the mechanism model used in the control synthesis. Also, the developed controller ensures high dynamic performance of the system. With the advancement of techonology and introduction of new types of robotic actuators (say new types of electro-mechanical motors or artificial muscles) into the system's control structure, the control scheme at tactical level will remain unchanged. The developed integral dynamic controller can be potentially applied in combination with intelligent control techniques and robotic vision, to control biped locomotion mechanisms in the course of fast walking, running, and even in the phases of jumping, as it possesses both the conventional position-velocity feedback and ground-reaction feedback. Performance of the control system was analyzed in a number of simulation experiments in the presence of different types of external and internal disturbances acting on the system.

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