Bio-inspired Control of Biped Robot Locomotion by Anthropomorphic Leg Impedance Modulation

Contribution to Control of Artificial Biped Gait

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Abstract—The paper addresses control synthesis of anthropomorphic adaptive biped gait with humanoid robots walking on compliant support surfaces. Adaptive impedance control of biped robots with a bio-inspired modulation of leg impedance parameters based on motion capture experimental measurements is proposed in the paper. Moreover, a complementary fuzzy regulator of biped robot dynamic balance based on feedback upon dynamic reactions is implemented within the robot controller to maintain gait stability, too. Corresponding experimental motion capture measurements with human test subject are considered in the paper to acquire natural principles of human locomotion and principles of leg impedance modulation. Corresponding knowledge-based algorithm for leg impedance modulation and better adaptation to different ground support conditions is proposed and verified through simulation by use of the model of a middle-size 36 DOFs humanoid robot MEXONE. Some characteristic closed-loop simulation results are given in the paper to verify advanced control performances.

Keywords—biped gait; adaptive control; leg impedance modulation; dynamic balance.

I. INTRODUCTION

During walking, running or jumping, leg muscles and tendons are being strengthened or relaxed alternately according to the physical phases of locomotion. As consequence, landing foot produces corresponding ground reaction forces through foot contact/impact to the ground, that transmit to the corresponding leg joints. In that sense, the term leg impedance represents a measure of how much a body structure resists motion when subjected to a given external force(s). It relates forces with corresponding velocities acting on a biomechanical system. The mechanical impedance is a function of the frequency of the applied force and can vary greatly over frequency. At resonance frequencies, the mechanical impedance will be lower, meaning less force is needed to cause a structure to move at a given velocity. Leg impedance has an important role in human locomotion. By modulation of leg impedance in a natural way, it is possible to produce different kinds of biped locomotion as well as to damp corresponding destructive impact/contact forces that represent perturbation to the system and can cause in-stability.

The adaptive control of biped robots with leg impedance modulation is proposed in the paper. It controls the impedance of the swing foot as well as the hip link [1]. The impedance control method has been successfully used for the robot manipulators [2] which interact with their environment. With locomotion, a biped robot is in contact with the ground with single or two feet. Only in running or jumping there are phases when humans or robots have no contacts with the ground and then they have to be considered as “flyers” [3]. Moreover, impedance control for bipedal locomotion is similar to the control method that a human uses for his locomotion. When human walks, he does not explicitly control the trajectory of his upper body but rather controls the muscle strength of his legs that support the upper body [1]. One also rather controls the trajectory of the swing foot in order to avoid obstacles such as bumps or in order to land the foot in a safe area, for example, avoiding a pot hole. In typical human locomotion, the leg muscles are repeatedly tensioned and relaxed depending on the gait phase [4]. Just before the contact of the swing foot with the ground, the leg muscle is relaxed to regulate and reduce impact, resulting in a very soft contact with the ground. Borrowing this idea from human locomotion, the paper suggests the parameters to be used in the impedance control to be also appropriately modulated depending on gait phase.

II. MODELING OF BIPED ROBOT LOCOMOTION

A. Modeling of Robot Rigid Body Dynamics

Let consider a biped robotic system of the anthropomorphic structure whose joints allow \( n \) independent motions. These joint motions (angles) form vector of the generalized coordinates \( q = [q_1 \cdots q_n]^T \) that describes completely the relative motion of the links. The base link (the pelvis in this case) is allowed to perform six independent motions in 3D-space [3]. Let the position of the basic link be defined by the three Cartesian coordinates \((x, y, z)\) of its mass center and the three orientation angles \((\varphi \text{-roll, } \theta \text{-pitch and } \psi \text{-yaw})\), forming the vector \( \mathbf{X} = [x \ y \ z \ \varphi \ \theta \ \psi]^T \). Now, the overall
number of DOFs for the system is \( N = 6 + n \), and the system position is defined by

\[
\mathbf{Q} = \begin{bmatrix} \mathbf{X} \quad \mathbf{q} \end{bmatrix}^T = \begin{bmatrix} x & y & z & \phi & \psi & \mathbf{q}_1 & \ldots & \mathbf{q}_n \end{bmatrix}^T
\]

(1)

It is assumed that each joint has an appropriate actuator. This means that each motion \( \mathbf{q}_j \) has its own drive – the torque \( \tau_j \). Note that there is no drive associated to the basic body coordinates \( \mathbf{X} \). The vector of the joint drives is \( \tau = [\tau_1 \ldots \tau_n]^T \), and the augmented drive vector (\( N \)-dimensional) is \( \mathbf{T} = [0_6 \quad \tau]^T = [0 \ldots 0 \quad \tau_1 \ldots \tau_n]^T \). The dynamic model of biped robot mechanism (humanoid) can be defined in the decoupled form according to [1,3]:

\[
\begin{align*}
\mathbf{H}_{\mathbf{X},\mathbf{X}} \ddot{\mathbf{X}} + \mathbf{H}_{\mathbf{X},\mathbf{q}} \dot{\mathbf{q}} + \mathbf{h}_\mathbf{X} &= 0_6 + \mathbf{J}_{\mathbf{X}}^T \mathbf{F} \\
\mathbf{H}_{\mathbf{q},\mathbf{X}} \ddot{\mathbf{X}} + \mathbf{H}_{\mathbf{q},\mathbf{q}} \dot{\mathbf{q}} + \mathbf{h}_\mathbf{q} &= \tau + \mathbf{J}_{\mathbf{q}}^T \mathbf{F}
\end{align*}
\]

(2)

Dimensions of the inertial matrices are: \( \mathbf{H}(N \times N) \), \( \mathbf{H}_{\mathbf{X},\mathbf{X}} (6\times6) \), \( \mathbf{H}_{\mathbf{X},\mathbf{q}} (6\times n) \), \( \mathbf{H}_{\mathbf{q},\mathbf{X}} (n \times 6) \), and \( \mathbf{H}_{\mathbf{q},\mathbf{q}} (n \times n) \). Dimensions of the vectors containing centrifugal, Coriolis' and gravity effects are: \( \mathbf{h}(N) \), \( \mathbf{h}_\mathbf{X}(6) \), and \( \mathbf{h}_\mathbf{q}(n) \). Vector \( \mathbf{h}(\mathbf{Q}, d) \) consists of two vectors: the vector of centrifugal and Coriolis' forces \( \mathbf{h}_{\text{cf}}(\mathbf{Q}, \mathbf{Q}, d) \) and the vector of gravity forces and moments \( \mathbf{h}_g(\mathbf{Q}, d) \). Dimension of the vector of ground reaction, external load and disturbance forces is \( \mathbf{F}(m \times 1) \).

Dimensions of the Jacobi matrix and its sub matrices are: \( \mathbf{J}(m \times N) \), \( \mathbf{J}_{\mathbf{X}}(m \times 6) \), \( \mathbf{J}_{\mathbf{q}}(m \times n) \). Vector \( \mathbf{d}(l) \) represents parameter vector including kinematical parameters (links’ lengths, positions of the links’ mass centers), as well as the corresponding dynamic ones (links’ masses, moments of inertia) of the robotic system. Model (2) is used in Section IV for synthesis of the impedance control algorithm.

B. Kinematical Model of Leg Motion

The general description of leg motion assumes three Cartesian coordinates of selected point of the foot link plus three orientation angles of the foot [3]: \( \mathbf{s}_f = \begin{bmatrix} x_f & y_f & z_f & \phi_f & \psi_f \end{bmatrix}^T \). Coordinates are defined with respect to the inertial coordinate system attached to the ground support. The subscript "\( f \)" is standing for the "foot link". The relation between the foot links coordinates \( \mathbf{s}_f \) and the leg position vector \( \mathbf{q}_l \) is given by:

\[
\mathbf{s}_f = \mathbf{s}_f(\mathbf{X}, \mathbf{q}_l, d)
\]

(3)

\[
\dot{\mathbf{s}}_f = \dot{\mathbf{s}}_f(\dot{\mathbf{X}}, \dot{\mathbf{q}}_l, d)
\]

(4)

\[
\ddot{\mathbf{s}}_f = \ddot{\mathbf{s}}_f(\ddot{\mathbf{X}}, \ddot{\mathbf{q}}_l, d)
\]

(5)

where \( \mathbf{q}_l \) is the corresponding \( 6 \times 1 \) vector of leg’s (right and left) joint coordinates, \( \mathbf{X} \) is a \( 6 \times 1 \) position vector of the hip (basis) link of robot mechanism defined in (1), \( \mathbf{J}_l = \frac{\partial \mathbf{s}_f}{\partial \mathbf{q}_l} \) is a \( 6 \times 6 \) Jacobian matrix of the foot link with respect to the basis link, and \( \mathbf{A}_f = \left( \frac{\partial^2 \mathbf{s}_f}{\partial \mathbf{q}_l^2} \right) \mathbf{q}_l^2 = \mathbf{J}_l \mathbf{\dot{q}}_l \) is a 6-dimensional adjoint vector.

III. NATURAL LEG IMPEDANCE MODULATION

For the purpose of research in this paper, the motion capture experiments were carried out. A 21 years old male subject of 1.73 (m) and 71(kg) weight, of normal physical constitution and functionality, is chosen (Fig. 1). The body parameters are identified combining the direct measurements, photometry and implementation of the anthropometry empirical relations given in [7]. The VICON-460 motion capture system with six high-resolution, fast (200 Hz) infra-red cameras was used for motion capture. Ground reaction forces were measured by two tension platforms with sampling frequency of 1.0 Ghz. The following variables are experimentally acquired from the human test subject: (i) body joint trajectories (Fig. 2), i.e. corresponding joint trajectories (ii) hip joint center trajectories and corresponding feet cycloids (heel, toe and foot tip trajectories, Fig. 3), and (iii) ground reaction forces/torques (Fig. 2) generated at the footsole. The obtained variables are used for identification of leg impedance characteristics (damping and stiffness coefficients) as well for analysis of anthropomorphic characteristics of human gait. A variety of walking experiments were performed and processed. Experimental results were used for the off-line processing and training of an appropriate artificial neural network architecture that was used afterward for fine tuning of a fuzzy inference
system (FIS) for the leg impedance modulation. The designed FIS for leg impedance modulation is used in this paper to control the legs’ motion of a middle size biped robot MEXONE presented in Fig. 4.

Figure 2. Snapshots of human gait obtained from motion capture system and corresponding ground reaction forces experimentally measured by two tension platforms

Figure 3. Foot cycloids and relative foot landing velocities of the right foot contour points with respect to ground support

IV. IMPEDANCE CONTROL OF BIPED LOCOMOTION

A. Strategy of Leg Impedance Modulation

A good biped robot control scheme should have the following capabilities. First, the desired trajectory of the swing foot should be tracked as accurately as possible in order to avoid obstacles. On the other hand, tracking of the upper body is not so much rigorous as that of the swing foot. However, maintaining a good balance and posture stability of the upper body is important having in mind that it carries a vision system (e.g. stereo cameras) on the head and that robot arms have to perform different service tasks. Second, footing on the ground should be safe and stable. An efficient control scheme would prevent the swing foot from being bounced from the ground during its landing on the support surface (ground). Foot bouncing from the ground, during foot landings, could cause instability in locomotion and thus should be ultimately avoided. Third, biped robots should be also capable of fast locomotion with a dynamic balance, for example, on a compliant surface or carpeted floor, on a surface with pebbles as well as on a flat rigid supports. Summarizing research results and practical experience of many research studies concerning implementation of different control strategies for dynamic biped locomotion [8], the impedance control strategies were found to be applied most frequently in the control of contemporary humanoid robots. Park proposed [1] an impedance control and corresponding switch-mode impedance modulation in particular phases of biped gait as well as in particular directions of locomotion. Both legs are controlled by impedance, where the desired impedances at the hip and swing foot are specified. The impedance parameters (damping factors) were changed depending on the gait phase. Stiffness of the legs was assumed invariable. The impedance control law is derived under the assumption that there exist contact sensors at the feet soles and force/torque sensors at the ankles so that the controller knows when a foot reaches the ground and how much the contact force/torque is generated at the feet. Both feedbacks (sensor information) are necessary for building a regulator of dynamic balance to be described in the next section, too.

This paper proposes that the impedance of the swing foot should be specified with respect to the ground. During the swing phases (SPs) and weight acceptance phases (WAPs), the impedance of the tip of the swing foot depends on the entire kinematical chain, which passes through the hip and terminates at the ground contact point of the support foot of other leg. This paper also proposes a way of adaptive modulation of the set of impedance model parameters to be used for the swing foot depending on its locomotion phase, i.e. whether it is in the SP, weight support phases (WSP) or in the WAP. The higher damping ratio, as it will be demonstrated, is used in WAPs than that in SPs and WSP in order to absorb impact energy in foot landings. Also, the leg in its WSPs, supporting the weight of the biped robot and propelling the hip and the upper body forward, is controlled based on the impedance model of the hip and upper body with respect to the foot on the ground. The
impedance model is selected so that the hip link follows its predetermined trajectory (e.g., natural cycloids) and moves forward. It should be stressed that the impedance of the hip link in the WSP phase depends on the entire chain up to the ground contact point or the supporting foot. The relations defining the impedance control algorithm of biped robot locomotion are presented in the text to follow.

### B. Control Synthesis

The impedance control is applied at the level of the inertial frame rather than the joint space, as the desired behavior of the biped robot at the global coordinate is needed. For that purpose, the model of biped robot mechanism (2) is used to design the control algorithm of the overall biped mechanism including hip link and swing foot impedance control as well as posture control of the upper body and robot arms. The vector form of the control algorithm is defined as:

\[
\tau = H_{q,0} \ddot{X}^* + H_{q,0} \ddot{q}^* + h_{q} - J_{q}^T F
\]  

(6)

where \( \ddot{X}^* \) and \( \ddot{q}^* \) represent corresponding \( 6 \times 1 \) and \( n \times 1 \) control accelerations to be defined in the text to follow. Vector \( \ddot{X}^* \) concerns with control of hip (basis) link motion while \( \ddot{q}^* \) concerns with biped robot joint motions including legs, trunk and arms displacements. The vector of control joint accelerations \( \ddot{q}^* \) has the following sub-vectors that correspond to the particular kinematical chains (legs, arms, and trunk) of biped mechanism.

\[
\ddot{q}^* = [\ddot{q}_{tr} \ddot{q}_{rl} \ddot{q}_{ll} \ddot{q}_{ra} \ddot{q}_{la}]^T
\]  

(7)

where “tr”, “rl”, “ll”, “ra” and “la” stands for trunk, right leg, left leg, right arm and left arm successively.

Suppose the desired impedance of the hip (basis) link, reduced to the center of it, is expressed in a form:

\[
M_{b}(X - X_0) + B_{b}(\dot{X} - \dot{X}_0) + K_{b}(X - X_0) = 0_{6}
\]  

(8)

where, \( M_{b}, B_{b}, K_{b} \) are the desired mass, damping ratio, and stiffness of the hip (basis) link, respectively. Impedance of the hip link in the single support phase depends on the entire leg chain up to the ground contact point center (case of foot multi-point contact) of the supporting foot. Control acceleration of the hip link \( \ddot{X}^* = \ddot{X} \) is calculated from (8) and is used in (6).

Suppose that the desired impedance of the leg in the swing phases (SPs) and the weight acceptance phases (WAPs) is expressed as:

\[
M_{l}(\dot{s}_f - \dot{s}^0_f) + B_{l}(\dot{s}_f - \dot{s}^0_f) + K_{l}(s_f - s^0_f) = -(F_i - F_i^0)
\]  

(9)

where super-index “0” denotes the desired (reference) value, \( M_{l}, B_{l}, K_{l} \) are matrices with respect to the desired mass, damping ratio and stiffness of the swinging leg, and \( F_i \) is the resultant vector of the ground reaction forces at the considered foot link. In order to make it possible to shift the load from the one leg to another one, as the second leg gradually takes the weight of the biped robot mechanism in the WAP, reference forces/torques \( F_i^0 = [F_{1x}^0 F_{1y}^0 F_{1z}^0 0 0 0]^T \) at the foot sole should be selected properly (e.g., trapezoidal profile to be used).

Having in mind the non-linear relation (5), which maps the leg coordinates \( q_i \) from the joint space to the Descartes coordinates of the corresponding foot \( s_i = [x f y f z f \varphi_f \theta_f \psi_f]^T \) in task space, then (5) can be re-written in a form:

\[
\ddot{q}_i = J_i^{-1}(q_i, d) \cdot \dddot{X}_i - J_i(q_i, d) \dddot{q}_i
\]  

(10)

The explicit relation between the leg impedance and the corresponding joint coordinates is possible to be derived by combination of (8), (9) and (10).

The control accelerations (7) for the right \( \ddot{q}_{rl} \equiv \ddot{q}_l \) and left leg \( \ddot{q}_{ll} \equiv \ddot{q}_l \) are determined by use of (10), providing desired hip link and leg impedance of the biped robot. The rest of the control accelerations given in (7), that ensure posture stability and accurate robot arm trajectory tracking are determined from:

\[
\ddot{q}_{ch}^* = \ddot{q}_{ch}^0 - K_{ch} (q_{ch} - q_{ch}^0) - K_p (q_{ch} - q_{ch}^0)
\]  

(11)

where the subscript “ch” denotes one of the following kinematical chains (trunk “tr”, right arm “ra” or left arm “la”) that do not participate in locomotion but are of importance for performing robot service tasks. The \( K_p \) and \( K_d \) represent corresponding positional and differential control gain matrices in a diagonal form of dimension \( 6 \times 6 \). The elements of matrices can be determined either by pole-placement method or in frequency domain (8).

Set of impedance parameters, including basis (hip) link impedance \( (M_{b}, B_{b}, K_{b}) \) and swing leg impedance \( (M_{l}, B_{l}, K_{l}) \) defined in (8) and (9) are calculated using the following relations:

\[
K_s = M_s \cdot \omega_s^2, \quad B_s = M_s \cdot 2 \zeta_s \cdot \omega_s,
\]

\[
\omega_s = 2 \pi \nu_s, \quad \zeta_s = 1.
\]  

(12)

\[
K_i = M_i \cdot \omega_i^2, \quad B_i = M_i \cdot 2 \zeta_i \cdot \omega_i \cdot \text{diag} \{b_{1s} \ldots b_{bs}\},
\]

\[
\omega_i = 2 \pi \nu_i, \quad \zeta_i = 1, \quad b_{ij} \in \{b_{ij}^{\text{min}}, b_{ij}^{\text{max}}\}
\]  

(13)

where the inertial matrices of the hip and leg impedance \( M_{b} \) and \( M_{l} \) are assumed to be of constant values. Corresponding particular damping \( (B_{b} \) and \( B_{l} \)) and stiffness matrices \( (K_{b} \) and \( K_{l} \)) are calculated from (12) and (13). The damping
adjustment factors $b_{ij}$ (for the particular directions of motion $i=1,...,6$ i.e. x, y, z, roll, pitch and yaw) serve to modulate robot leg impedance given in (9); $\varsigma^l_b$ and $\varsigma^l_t$ are corresponding relative damping factors while $V^l_b$ and $V^l_t$ are corresponding hip link and leg impedance frequency bandwidth of the impedance controller assumed to be varied within the range that fits natural frequencies of mechanical subsystems such as trunk and robot legs. Bearing in mind that the ground compliance and gait parameters can vary significantly during locomotion, the impedance parameters $b_{ij}$ should be changed consequently. Modulation of damping factors provides better leg adaptation to the variable gait conditions. The adjustment factors $b_{ij}$ are proposed in the paper to be calculated by implementation of a fuzzy inference system (FIS) of Mamdani type. The input variables of the proposed FIS for leg impedance modulation are (Fig. 5): (i) relative foot “landing speed” $\dot{z}_l$ with respect to the support surface, (ii) relative ground reaction force deviation “grf deviation” $(F_z - F^0_z)/F^0_z \cdot 100\%$ with respect to the nominal value $F^0_z$ defined in advance, and (iii) ground reaction force-rate “grf rate”, i.e. contact force gradient expressed in the form $(dF_z/dt) \cdot 1/F^0_z \cdot 100\%$. The mentioned input variables are defined with respect to the foot motion in the conditionally vertical plane, perpendicularly to the ground support. The Sigmoid curve membership functions are assigned to the input variables as well as to the output one. The output variable “damping factor” of the proposed FIS (Fig. 5) for leg impedance modulation regards to the amplitude of the adjustment factor $b_l$ that modulates leg damping characteristics in three particular directions vertical-z, roll-$\varphi$ and pitch-$\theta$ that are related to foot point impacts. In the rest directions, the impedance controller keeps constant damping factors. The mentioned membership functions (MFs) are used to model non-linear character of leg impedance. Two determining parameters of the considered MFs locate the extremes of the sloped portion of the curves (see fuzzification block in Fig. 5). The MFs are tuned using curve parameters obtained by implementation of appropriately artificial neural networks independently trained for particular input and output FIS variables. The non-linear character of the fuzzy MFs enables non-linear modeling of human leg impedance. Being the input and output variables of the designed FIS are normalized with respect to the particular maximal values, the identified non-linear model of human leg impedance can be simply scaled and mapped to any biped robot to control its leg impedance in an anthropomorphic way. Corresponding fuzzy rules of the FIS (Fig. 5) are designed in a way to satisfy the biological principles of changing leg damping characteristics.

V. SIMULATION EXPERIMENTS

Verification of the proposed adaptive impedance control of biped robot gait, defined by relations (6)-(13), is performed by corresponding simulation experiments. Aim to this goal, model parameters of the 36-DOFs (4 at the binocular head, 4 for each hand, 5 for each arm, 2 at pelvis, and 6 at each leg) MEXONE biped robot [9] of 1.026 (m) height and 8.36 (kg) weight is assumed. Corresponding HRSP software toolbox [10] is applied for simulation humanoid robot kinematics and dynamics. Simulation experiment, presented in this paper, regards planar motion in sagittal direction moving with forward speed of 0.60 (m/s), 0.40 (m) step size, and 0.075 (m) height of swinging leg. The proposed adaptive impedance control with leg impedance modulation, defined by (6)-(13), is implemented. Simulation results are presented and analyzed in the text to follow. Inertial impedance parameters are assumed to be: $M_b=10$ (kg), $M_l=5$ (kg). Corresponding impedance parameters $B_b$, $B_l$ and $K_b$, $K_l$ in (6)-(13) are determined based on the empirically-based frequency bandwidth characteristics $V^l_b = 4$ (Hz) and $V^l_t = 6$ (Hz) as well as varying the damping adjustment factor $b_{ij}$ (13) within the range soft-hard, i.e. $b_l \in (0,8,2,0)$. Selective impedance modulation approach is applied assuming that variable impedance should be set in the vertical-z, roll-$\varphi$ and pitch-$\theta$ directions of motion. In the rest of directions (sagittal-x, lateral-y and yaw-$\psi$), the damping factor is assumed to be $b_{ij} = 1$. Variable damping adjustment factors $b_{ij}$ are calculated by FIS aimed to provide leg impedance modulation as described in Section IV. The synthesized adaptive control ensures fine dynamic performances of biped gait including both – satisfactory dynamic balance as well as precise tracking of the hip link trajectory and reference feet cycloids. Adaptive impedance control algorithm provides biped robot a smooth gait without hard impacts (contact force peaks) as presented in Fig. 6. Ground reaction forces obtained in the sagittal $F_x$ and lateral $F_y$ directions (Fig. 6) include stiction and friction effects due to the compliance of ground support. Certain weak sliding of robot feet soles on the ground support appears as it is presented in Fig. 7. The footprints of the biped robot with the Zero Moment Point (ZMP) hodograph are presented in Fig. 7, too. The hodograph of the ZMP displacements proves that the

![Figure 5. Block-scheme of the fuzzy inference system for leg impedance modulation – structure and input/output variables; Fuzzy rules applied](image-url)
robotic system maintains dynamic balance during a considered planar motion. Concerning trajectory tracking precision, the proposed impedance controller (6)-(13) ensures satisfactory accuracy of robot motion with respect to the imposed nominal trajectory. Robot feet (Fig. 9) perform periodic anthropomorphic cycloids of maximal height of 0.075 (m) as reference value. The relative position (attitude) of robot swinging feet with respect to the ground support is kept within the desired range (tolerance). That means, the foot performs motion with high accuracy by keeping its longitudinal, lateral and vertical position in the range imposed by the task. Also, the attitude deflection of robot feet of swinging legs is minimal. The consequence of it is that the biped robot with the adaptive impedance control is capable to avoid obstacles in a safe and precise manner. The robot feet keeps tempo and there is no delay due to changing swinging leg speed.

The hip link motion performs precise tracking of the reference motion of hip-link center (Fig. 10), too. The body attitude of biped robot is kept in the vicinity of its reference position during motion. Proposed control algorithm ensures posture stability, i.e. minimal upper body attitude deflection that is of crucial importance for robotic service tasks.

VI. CONCLUSIONS

The main contribution of the paper concerns with design of novel, biologically-inspired, adaptive impedance control algorithm applied to biped robot locomotion. Leg impedance modulation is performed in an anthropomorphic way, implementing biological principles of leg impedance modulation based on gait conditions and proprioceptive feedbacks on dynamic reactions upon biped robot legs. Impedance modulation does not depend on the gait phases only (as considered in [1]) but also on real gait conditions and dynamic reactions changing in real-time. The impedance parameter (leg damping coefficient) is adjusted in real-time (continually) as the humans do it. Paper explains how the adaptive impedance control is implemented, how to identify...
the variable parameters in order to achieve high (but not optimal in sense of energy dissipation) dynamic performances of the system. Artificial bio-inspired (anthropomorphic) gait is concerned in the paper, too, using results obtained by motion capture with human test subjects. The efficiency of the control strategy proposed in the paper is verified by simulation examples concerning planar motion of biped robot. The proposed adaptive impedance control algorithm is planned to be implemented with the MEXONE biped robot controller in the forthcoming period.

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