Toward a Human-like Locomotion: Modelling Dynamically Stable Locomotion of an Anthropomorphic Robot in Simulink Environment

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Abstract: In the near future anthropomorphic robots will turn into an important part of our everyday routine. To successfully perform various tasks these robots require stable walking control algorithms, which could guarantee dynamic balance of the biped robot locomotion. Our research is focused on the development of locomotion algorithms which could provide effective anthropomorphic walking of a robot. As a target robotic platform we utilize an experimental model of a human-size robot - a novel Russian robot AR-601M. In this paper we introduce AR-601M robot and present a model of a biped robot with 11 DoF which simulates a simplified AR-601M robot. The simulation model is implemented in Matlab/Simulink environment and uses walking primitives in order to provide a dynamically stable locomotion.

1 INTRODUCTION

In the last century robotics was mainly the focus of interest of Ministries of Defense and Space, university research laboratories and a few giant corporations. One of the most critical tasks was to develop multi-terrain robots in order to operate in dangerous environments (e.g., nuclear, chemically or biologically polluted environments) and to perform various functions in order to support humans in search and rescue operations, military and space missions. Today robotic products are rapidly turning into consumer's goods - yet not affordable and available to all groups of the population. But that is just a question of time, and in the coming decades we will see the wide-spread of domestic, social and educational robots. Such robotic systems will replace people in various operations in unfriendly environments and at home, and thus require comparable to a human skills of locomotion inside buildings together with the ability to operate the devices which were originally created for a human. To guarantee the comparable to a human skills, multi-functionality and flexibility, an anthropomorphic structure of a robot would be required. Bipedal locomotion of an anthropomorphic robot provides mechanisms to step over obstacles, climb stairs and ladders, and walk on uneven terrain - the activities which could not be fully performed by a wheeled or a tracked robot. Anthropomorphic domestic robotic assistants would also facilitate human-robot interactions and social activities, which often require the robot to work in a direct physical contact with a person, to master safe (Amirabdollahian et al., 2013) and acceptable by a human social behavior, and to be visually acceptable by a human (Fink, 2012). Therefore anthropomorphic robotic systems with stable anthropomorphic movement dynamics and high-energy efficiency become critical. During the decades of bipedal locomotion research a number of different approaches targeting for stable locomotion were developed, and Section 3 presents a brief overview of the existing approaches. Unfortunately, due to serious difficulties with balance preserving and redundant degrees of freedom (Wu et al., 2009), walking of humanoid robots is still far from achieving a comparable to a human level of anthropomorphism and reliability (Wright and Jordanov, 2014).

The objectives of our research are to develop solutions of dynamically stable walking for a biped robot AR-601M. In order to reduce the time of software development with the real robot and to provide system debugging on early stages of algorithm development, it is essential to create a relevant simulation model which takes into an account physical properties of the robot and its interaction with the environment. Dynamical mathematical models for legged locomotion - for animals (Ijspeert, 2008), insects (Holmes et al., 2006) or humans (Zajac et al., 2003) - help to simu-

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late the balance-based locomotion algorithms behavior prior to experiments with a robot and also may give clues on ”healthy” or ”pathological” gaits. In this paper we introduce current stage of our study and present the simulation model of the biped robot AR-601M in Matlab/SimMechanics[1].

The rest of this paper is organized as follows. Section 2 introduces Russian humanoid robot AR-601M. Section 3 considers the theoretical background of a biped robot locomotion methods. Section 4 presents a designed Simulink model of AR-601M robot. Finally we conclude and discuss the future steps of our research in Section 6.

2 SYSTEM SETUP

This section describes the AR-601 robot as the holistic system setup, which is used for dynamically stable robot locomotion model development.

The anthropomorphic robot AR-601M (fig. 1) is being developed by Russian company ”Android Technics”[2]. It is a full-scale anthropomorphic robot system with the height of 144 cm and the weight of 60 kg, which correspond well with an average human body parameters[3].

Figure 1: Testing anthropomorphic robot AR-601M, the shell is removed.

Table 1: Technical characteristics of AR-601 robot.

Parameter	Value
Height	1442 mm
Mass	60 kg
Battery life	3 hours
Sensors	IR × 16 Camera × 3 Lidar × 2 Accelerometer × 6 Magnetic encoder × 30
Degrees of freedom	Total: 69 Active: 45
Type of Motors	Electrical
Material of body	Plastic
Battery type	Li-FePo
Network interfaces	Wi-fi, Ethernet

The robot has a lightalloy frame with power electric motors, two robotic arm-manipulators and two legs, which allows having up to 69 degrees of freedom (DoF), of which six DoFs belong to each leg. To control the robot movement there are 26 large and 12 small electric motors with STM32F103T8U6 controllers and the communication protocol provides data about all motor states, pressure values in robot’s feet and on-board gyroscopes. The robot has a built-in multi-sensor system, speech recognition and synthesis systems. Table 1 presents in details some of the important parameters of AR-601M which influenced our model and algorithms development.

The robot locomotion control is carried out by setting the joint angles for motor’s rotation along with angular velocities and accelerations. In addition, each joint could be controlled directly with torque output commands. Therefore, MATLAB Simulink can be used to reproduce an interface of communications protocol and simulate on-board robot control system and input signals to control electric motors. To do this within the Simulink model, simulated signal packages are sent to the motors in synchronous mode and the controllers manage the response packages from sensors. Furthermore, it makes possible to set the coefficients of the PID controller with specially simulated commands or even to simulate the particular commands like, for example, the brake coupling for fixing the drives position with knee and hip joints locking. However, in common case, it is sufficient to set the rotation angles for each joint and ignore particular mechanisms of motor control.

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[1] Multibody Simulation - SimMechanics, http://www.mathworks.com/products/simmechanics/

[2] Androidnaya Tehnika (Android Technics), AR-601M belongs to a generic AR-600 series of robots, http://en.npo-at.com/products/ar-600/

[3] In human robot interaction in order to maintain a clear master-slave relationship between the two parties it is important that a robot is not emitting any kind of threat to a human and this requirement is particularly embodied in lower than an average human height of the robot.

3 ON BIPEDAL ROBOT LOCOMOTION MODELLING

This section familiarizes the reader with popular models of biped robot locomotion modelling and methods for robot motion control.

3.1 A Bipedal Robot Model

The widely utilized strategies for simulating a biped robot are to use a model of inverted pendulum with or without a spring.

For **Inverted pendulum** or **linear inverted pendulum model** a biped robot acts as an inverted pendulum, because the center of mass (CoM) of the robot is localized in the upper body part. When the biped robot is doing a step, its swinging leg is similar to an inverted pendulum whose massless rod connects the supporting foot to the CoM of the robot (Stephens and Atkeson, 2009). As an illustration, this approach had evolved in the following models: virtual height inverted pendulum model, two masses inverted pendulum model, multiple masses inverted pendulum model, gravity compensated inverted pendulum model, etc. (Siciliano and Khatib, 2008)

Spring loaded inverted pendulum model is one of the best and simplest approximation that describes the spring-like leg behavior of human and animal walking or running (Garofalo et al., 2012). Spring loaded inverted pendulum is represented by a point mass that is attached to a massless spring with resting length and leg stiffness.

The important question is what approaches to the biped robot locomotion control should be applied in order to supply energy efficiency and acceptable locomotion speed while maintaining stability of the robot. Next, we briefly describe a number of methods, which are broadly applied for biped robot locomotion control by various research teams. According to (Manchester et al., 2011) all the existing humanoid bipedal walking robots could be roughly divided into two groups: ZMP-controlled ones and passive-dynamic walkers.

3.2 Approaches for Bipedal Robot Locomotion Control

Zero moment point (ZMP) is a theoretical model of biped locomotion where ZMP is defined as a point in which all the forces and moments can be replaced with a single force and a single moment respectively (Vukobratovic and Borovac, 2004). In other words this method defines a special point where the sum of horizontal inertial and gravitational forces equals to zero (Erbatur and Kurt, 2006). In order to maintain biped robot balance its ZMP should lie within the boundaries of a predefined stability region. This approach plays a role of a criterion in the stability analysis of biped robot locomotion and could be considered as a dynamic analogue of CoM or center of gravity (CoG) criterion for static stability analysis (Magid et al., 2011). ZMP approach defines trajectory of robot bodies without considering the load of each particular joint which causes poor energy efficiency of the locomotion.

Passive walking method is based on the body's momentum. A biped robot which is actuated by this method usually does not have any motors that produce forces for leg motion and the robot walks on an inclined slope without applying any force (McGeer, 1990). It is rather efficient for controlling robot locomotion because it creates movements in a similar way a human does, but due to low stability for external disturbances, this approach is not broadly used (Iribe and Osuka, 2006).

Walking primitives is an approach which generates trajectories for the joints. Usually walking primitives are calculated offline a-priori and next locomotion planning algorithm generates a sequence of motions as a combination of these predefined walking primitives (Denk and Schmidt, 2003) in order to move from the current posture and location to the goal location. The main assumption in this approach is that before and after applying a walking primitive accelerations and velocities of all joints are equal to zero, and therefore zero moment point always resides within a support polygon (Magid et al., 2008). As an example, a walking primitive can be realized by replacing the center of pressure from one leg to another. In order to combine two walking primitives together the initial state of the second primitive should be the end state of the previous one. This requirement is referred as a precondition and a post-condition of a walking primitive. Concatenating together several walking primitives is used to generate locomotion of a biped robot. This paper applies walking primitives approach which is further described in Section 4.

Artificial neural networks approach is used to learn the nonlinear dynamics of biped robot locomotion using a neuroadaptive control algorithm and the robot achieves optimization criterion of dynamic balance, such as ZMP. Given approach is broadly used - for example, Boston Dynamics uses this approach for Atlas robot locomotion algorithms (Atmeh et al., 2014). Major drawback of neural networks that makes them less practical for real-time control applications are the exponential growth of the number of parameters as a large-scale system becomes more complicated.

Full-body posture goal approach to path planning for humanoid robots computes dynamically-stable, collision-free trajectories from full-body posture goals (Kuffner et al., 2001). This method performs a search through configuration space of the robot in order to find a collision-free path to the goal posture while keeping dynamic balance.

Dimension reduction techniques serve for reducing calculation time: as a robot should make a decision on a next state within a limited time, a significant calculation time may become a reason of an algorithm's failure. Thus reducing dimension of locomotion equations directly influences feasibility of a locomotion algorithm. Those techniques decrease dimension of variables, which are used in the equations that describe control algorithms of a robot or even could reduce the number of such equations (Stilman et al., 2005).

4 MODELLING A STABLE BIPED ROBOT LOCOMOTION IN SIMULINK

Simulations became an important tool in robotics research. It helps to create advanced designs, evaluate new control algorithms and investigate a wide range of solutions for complicated problems. Significant advantage of such simulations is that there is no need of constructing or modifying a real robot, whereas simulated design solutions and experimental conditions depend only on researcher's creativity. Numerous software solutions for modeling multi-body dynamical systems have been created specially for robotic simulations, such as Gazebo[4], V-Rep[5], Matlab/Simulink and others. The later provides efficient tools for modeling and simulating mechanical systems (e.g., SimMechanics tool) which save significant time and effort for researchers. SimMechanic uses the standard Newtonian dynamics differential equations and simulates 3D translational and rotational motion by predicting the future state of a system from the current state. SimMechanics has a great number of tools to specify geometry, trajectories, mass distribution, constraints and instruments to initiate and measure motion, providing quite simple modeling of an anthropomorphic robot (bodies, joints, and external forces).

The equations of motion of a multibody system can be written in the following descriptor form:

$$\dot{q} = \tilde{H} v \tag{1}$$

$$M(q)\dot{v} = f(t,q,v) + \tilde{H}^T(q) G^T(q,t)\lambda \tag{2}$$

$$g(q,t) = 0 \tag{3}$$

where t represents time, q is a vector of configuration variables; H is a kinematic relationship matrix between the velocity variable v and $\dot{q}$ so that $v = H(q)\dot{q}$ with matrix $\tilde{H}$ denoting the right inverse of H; $M(q)$ is a mass matrix; $f(t,q,v)$ represents the contribution of centrifugal, Coriolis, and external forcing terms; $g(q,t)$ is a constraint equation and $G(q,t) = \partial g/\partial q$ is a constraint Jacobian; λ represents the vector of Lagrange multipliers associated with the constraint forces (Wood and Kennedy, 2003).

In (Velasquez-Lobo et al., 2013) the authors demonstrate an example of a biped robot model design and its locomotion verification with SimMechanics tool. Their model consists of five rigid bodies: a torso (modelled as a parallelepiped) and identical cylindrical shanks and thighs. These bodies are connected with revolute joints with a single rotational DoF in each joint and which sum up to 4 DoF in total. Unfortunately, such model simulates only the bottom part of the robot with its torso moving only in a sagittal plane relatively to the fixed coordinate system without rotation (2 DoF); this creates artificial conditions which prevent the robot from falling down.

In this paper we present a biped robot model which is free from the above mentioned limitations. The following simulation steps were performed using SimMechanics:

- Specify geometry of robot parts and their inertial properties
- Create links between the robot part - connect the bodies with rotational joints
- Set up ground reaction forces
- Provide reference signal for positions of each joint
- Start simulation, calling the Simulink solvers
- Visualize the model

Specifying robot geometry begins with defining a number of links and joints. Our current simplified robot model consists of twelve bodies, which are connected with revolute joints for knees, ankles, hips (one rotational DoF) and fixed (non-rotating) joints for a neck, elbows and shoulders. The torso and feet have a shape of a parallelepiped, a head is a sphere, and all other bodies are cylinders; the body parameters are described in details in Table 2. With regard to a global fixed coordinate system the torso has 3 DoF in sagittal plane: a rotation and 2 translations in vertical and

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[4] http://gazebosim.org/

[5] Coppelia Robotics, http://www.coppeliarobotics.com/

horizontal directions. Figure 2 shows the model structure. SimMechanics block diagram of the whole robot and its leg are shown in Fig. 3 and Fig. 4 respectively.

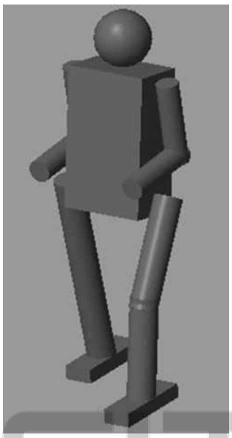

Figure 2: The robot model in Simulink.

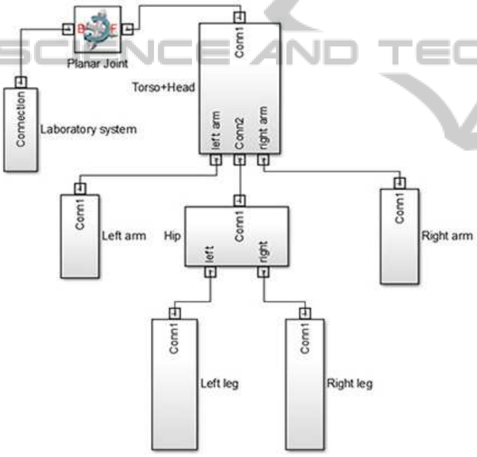

Figure 3: SimMechanics block diagram for the biped robot.

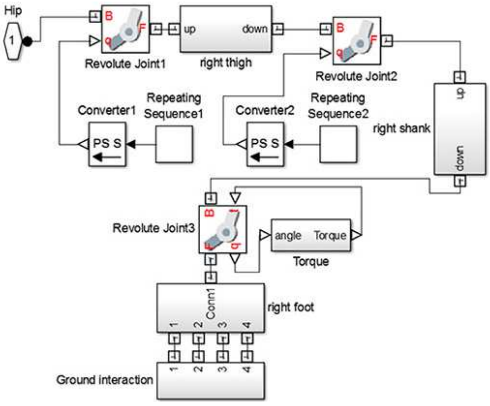

Figure 4: SimMechanics block diagram for the leg.

Table 2: Link parameters.

Torso parameters	
a, m	0.3
b, m	0.2
c, m	0.5
Mass, kg	30
Shank and Thigh parameters	
R, m	0.05
Length, m	0.4
Mass, kg	3.14
Head parameters	
Radius, m	0.1
Mass, kg	2.1
Upper and lower arm parameters	
R, m	0.01
Length, m	0.3
Mass, kg	0.75
Foot parameters	
Width, m	0.1
Length, m	0.3
Height, m	0.05
Mass, kg	1.5

Definition of ground contact forces is a very important issue in biped robot simulation and should be carefully modeled. When robot's feet touch the ground, normal and tangential forces are applied. There are several different approaches to calculate these forces. In the current work foot-ground interaction was modeled through a linear system with damping and stiffness. The following equation represents normal forces:

$$F_n = -k_n y - b_n \dot{y} \tag{4}$$

where y is the coordinate of the leg tip (y=0 corresponds to ground surface), k_n in the elastic constant and b_n is the damping coefficient. Normal force applied only when $y \leq 0$ (i.e. when the leg touches the ground). In order to avoid leg sticking F_n is limited to positive values only.

The following equation represents tangential force:

$$F_t = -b_t \dot{x} \tag{5}$$

where b_t is the tangential damping coefficient. Similarly to normal force, tangential force is applied only when $y \leq 0$. The ground coefficients k_n, b_n, b_t should be large (Table 3) in order to guarantee acceptable small penetrations of feet below ground level (the responsible for penetration coefficient is k_n) and reasonably fast damping of contact velocity (the responsible for damping coefficients are b_n, b_t). Equation 5

Table 3: Ground parameters (coefficients).

Coefficient	Label	Value / Units
penetration	k_n	1000000 N
normal damping	b_n	10000 (N*s)/m
tangential damping	b_t	1000 (N*s)/m
friction	μ	10

works perfect at leg landing, whereas at leg raising a so-called sticking effect emerges: we cannot provide strict vertical movement and have a horizontal component of velocity, which results in large tangential force. To avoid this sticking effect, the absolute value of tangential force should be limited to μF_n, where μ is a friction coefficient. At leg landing normal force F_n value is large, so the tangential force will be large enough to prevent the robot from sliding. At leg raising normal force F_n is small enough to avoid sticking. As far as the robot moves only in sagittal plane, there are no contact forces in $\vec{Z}$ direction.

There are several ways in SimMechanics to activate robot locomotion. The simplest one is to set positions of revolute joints. SimMechanics module calculates necessary torques to achieve desired angles in joints at each time step. These nominal trajectories can be set up a-priori, e.g., by utilizing motion capture system. In our work we realized dynamically stable robot motion using the method of walking primitives described in Section 3.2. It means that robot movement is divided into identical periods with walking primitives, at the beginning and at the end of which the robot returns to the same position. The leg movement pattern is the same in each primitive and can be divided into four phases (assuming generically that the step primitive starts from the left foot): (1) lift the left foot by specifying desired angles for hip and knee joints; (2) perform the inverted pendulum motion until the left foot touches the ground; (3) move the right foot forward by specifying the joint angles which make the knee and the hip joint angles equal to zero; (4) damp forward motion by applying torque in the ankles. Next, the same phases are repeated starting the step from the right leg. The input signals for the knee and thigh joint positions of the robot's legs are shown in Fig. 5– 8.

In the last walking phase the robot's forward motion is damped by applying torque in ankles when hip and knee joint angles become zero. The value of torque is calculated according to the following equation:

$$T = -c\phi - d\dot{\phi} \qquad (6)$$

where ϕ is the ankle joint angle, c=10 is stiffness, d=4 is the damping coefficient. Equation 6 is a standard representation of damping oscillations. As far as oscillations cannot be damped simultaneously, a pause $\triangle t$ is required before starting new movement with another leg.

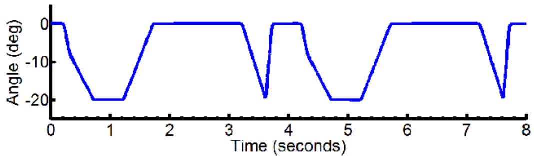

Figure 5: The input angle for the right knee.

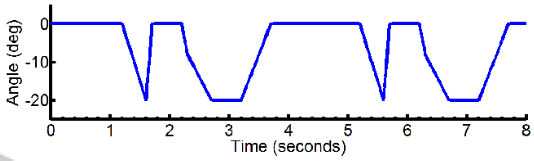

Figure 6: The input angle for the left knee.

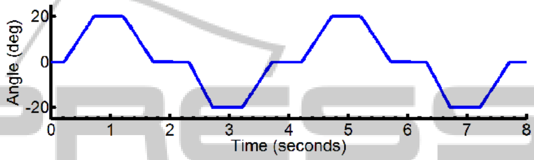

Figure 7: The input angle for the right hip.

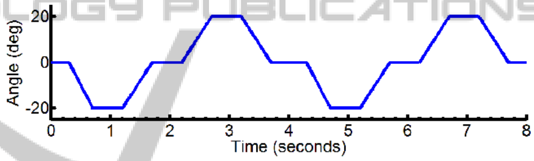

Figure 8: The input angle for the left hip.

5 SIMULATION RESULTS

To solve differential equations described above, the Simulink solver method ”ODE 23t” was used. Fig. 9 shows a sequence of the biped robot frames at different time while performing a single step. The smooth character of simulated robot walking illustrates reasonable settings for the angle positions of the joints and contact forces within the model. The horizontal locomotion of the torso center with the mean robot velocity of 0.3-0.4 m/s is shown in Fig. 10, demonstrating the periodical body movement during two second time period. At the beginning of each motion period the body velocity is zero. Torque values in the hip and the knee joints obtained from the simulation are shown in Fig. 11-14, which help to estimate motor characteristics.

The simulation shows that maximum torque is approximately 500 N*m in the thigh joint and 300 N*m

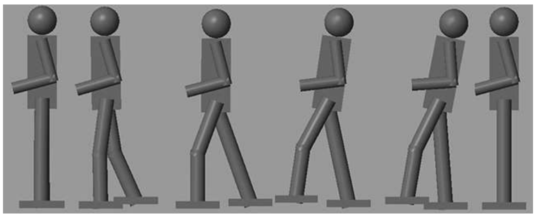

Figure 9: A single step of the biped robot. The robot moves from right to left as the time passes.

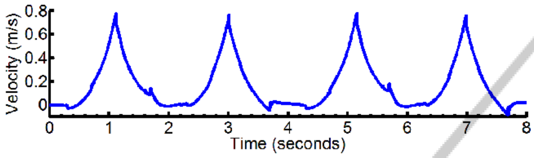

Figure 10: Horizontal velocity of torso.

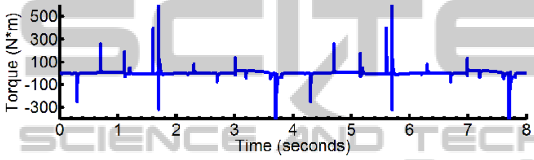

Figure 11: Torque in the left knee.

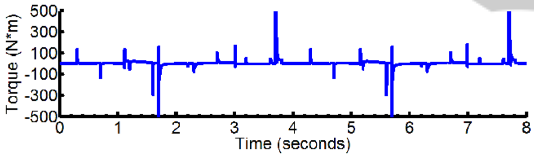

Figure 12: Torque in the right knee.

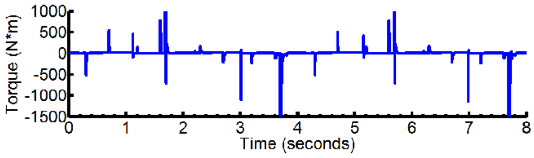

Figure 13: Torque in the left hip.

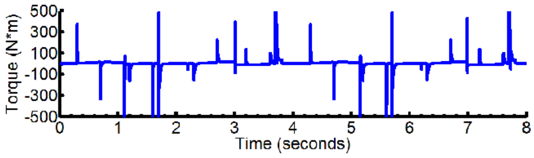

Figure 14: Torque in the right hip.

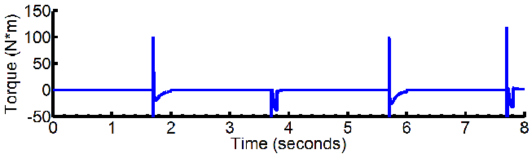

Figure 15: Torque in the left ankle.

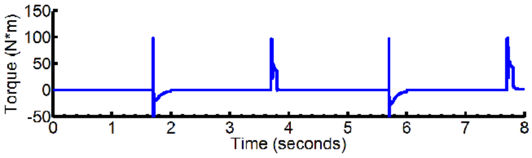

Figure 16: Torque in the right ankle.

in the knee joint. At the same time we see discontinuous jumps in calculated torque values, which are caused by discontinuities in ground reaction forces. Torque values in ankles are shown in Fig. 15 and Fig. 16. As it was expected, torque is applied only in the last phase of robot's motion in order to damp robot's movement. In our work the duration of one walking primitive is 2 seconds with a pause of $\triangle t = 0.5$ seconds between the primitives.

6 CONCLUSIONS AND FUTURE WORK

Our research is focused on creating effective human like locomotion for the novel anthropomorphic human-size Russian robot AR-601M. In this paper we introduced AR-601M biped robot, and presented its simplified model with 11 DoFs. The simulation model has been implemented in Matlab/Simulink using SimMechanics tool. This model uses walking primitives in order to provide a dynamically stable locomotion and serves as a starting point for the stable bipedal locomotion algorithms development for the AR-601M robot. The smooth character of simulated robot walking with the mean velocity of 0.3-0.4 m/s, reasonable settings for the angles of joints and contact forces illustrates the suitability of the proposed robot model.

Next we are going to extend this simplified model by increasing the number of DoFs (i.e. the number of robot joints) in order to match the simulation robot model to the exact kinematic structure of AR-601M. To achieve AR-601M anthropomorphic walking, the human walking data will be acquired and analyzed by Motion Capture (MoCap) system with the key features detection for a human gait. They will be initially mapped to the AR-601M locomotion within Matlab/Simulink simulation and then into the real robot gait together with the adaptive gait generation algorithm with the ZMP control. To apply these algorithms with a real robot it is also required to develop algorithms for sensory data collection and processing; in turn, these modules will provide input for decision-making and control actions computation algorithms.

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