Towards Robot Fall Detection and Management for Russian Humanoid AR-601

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Abstract. While interacting in a human environment, a fall is the main threat to safety and successful operation of humanoid robots, and thus it is critical to explore ways to detect and manage an unavoidable fall of humanoid robots. Even assuming perfect bipedal walking strategies and algorithms, there exist several unexpected factors, which can threaten existing balance of a humanoid robot. These include such issues as power failure, robot component failures, communication disruptions and failures, sudden forces applied to the robot externally as well as internally generated exceed torques etc. As progress in a humanoid robotics continues, robots attain more autonomy and enter realistic human environments, they will inevitably encounter such factors more frequently. Undesirable fall might cause serious physical damage to a human user, to a robot and to surrounding environment. In this paper, we present a brief review of strategies that include algorithms for fall prediction, avoidance, and damage control of small-size and human-size humanoids, which will be further implemented for Russian humanoid robot AR-601.

Keywords: Robot control · Humanoid robots · Safety · Humanoid robot fall · Safe fall · Fall prediction · AR-601

1 Introduction

Humanoid robotics is still considered a rather a young research field with many research challenges. While industrial robots are being widely used in manufacturing and their technology have reached high level of maturity with a variety of robots available from different manufacturers, only a few humanoid robots are currently commercially available. Most of full-size humanoids are built on customer request and come with a high price tag. Even though these humanoids share majority of their components (e.g. harmonic drive gears, controllers, sensors etc.), the systems differ significantly.

Humanoid robot locomotion is an extremely challenging research field as keeping stability during standing straight and locomotion is a necessary requirement for all applications of such robots. To address this issue problem of dynamically stable biped locomotion received significant attention over the last decades with some promising results [26–29].

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Biped humanoid robots have several advantages over wheeled mobile robots as they can step over obstacles and go up and down stairs. On the other hand, a bipedal robot has a major disadvantage – it may fall over and then get seriously damaged, injure people or destroy surrounding objects. Today this, together with high power consumption, is the most significant barrier for practical application of humanoid robots. Therefore, humanoid robots could not be entirely integrated in our society as everyday human assistants and companions unless this problem is solved.

There is a number of general approaches to solve this issue. First approach, Robot Hardware Design, deals with robot hardware; it concentrates on engineering robots' hardware in a way that it could survive a fall over due to resistant materials usage, shock-absorbing structures, etc. Second approach, Fall Detection, emphasizes importance of detecting when a fall is imminent in order to avoid such situations. Third approach, Fall Management, proposes a special fall sequence for reducing robot body damage or damage to objects in vicinity.

Fall avoidance strategies are an attempt to reduce fall frequency. When a fall does occur, fall damage control strategies could potentially minimize robot damage and/or damage of its environment. As humanoid robots are generally heavy, robot fall generally results in its serious damage or causes various damages to an object that is hit by the robot. Particularly, as an upper body of a humanoid robot is positioned relatively high when the robot moves, stands or performs some operations in straight vertical pose, the damage is likely to be very substantial. Therefore, it is desirable for a humanoid robot to minimize any damage, which the robot or an object hit thereby suffers when the robot turns over. While falling motion control reduces the robot damage, landing impact may still damage its parts if experiments are repeated over again to reevaluate control parameters. Therefore, most researchers have to substitute real experiments with simulations in order to reexamine and refine the control.

Fall damage minimizing received an interest in human biomechanics and have been extensively studied for the past decades [5–8]. Even though biomechanics experience and contribution are valuable for a fall detection and management, and provides significant insights, we should be aware of the limits that are imposed by differences between biology and mechatronics, which emphasize that biomechanics results could not be directly applied to robots. For example, behavior of humans during a fall evolved with an instinct to save high-value regions of the body first, firstly protecting a head, a frontal face, or any limb that was ever injured previously. This may be applicable with corrections for a humanoid robot to protect an area of essential circuitry. There are also differences in the materials of the body and motor control between a robot and humans, which makes direct transfer impractical.

The rest of the paper is organized as follows. Section 2 presents fall detection approaches for small size and human size humanoids. Section 3 deals with fall management. Section 4 discusses our future work proposal on fall detection and prevention for AR-601. Finally, we conclude in Sect. 5.

2 Fall Detection

The main objective of fall detection algorithms is to discriminate between fall events and normal activities of a robot. If during an operation, a humanoid robot suffers a strong disturbance under external force or torque, and its controller generates a correction motion that cannot actually be completed on time or performed in general, then the robot might fall even though the stabilizing control keeps operating.

To detect a fall Renner et al. in [9] used attitude sensors and indicators that triggered integrated into a control system robot reflexes. They estimated model parameters from an ideal gait sequence and used deviations that were calculated from the robot sensory data in real time as an instability indicator, which triggers recovery process.

Ogata et al. [10] proposed fall prediction methods that are based on a predicted Zero Moment Point (ZMP). The predicted ZMP is estimated by evaluating a performance limitation of ZMP feedback control, and the robot applies the predicted ZMP to detect imminent falls and to select correction motions. To further improve fall detection procedure Ogata et al. used discriminant analysis of experimental walking data labelled as fall and non-fall in order to construct a classifier [11].

Karssen et al. used multi-way principal component analysis (MPCA) in a simulation to predict the fall [12]. The method was able to predict whether the model is going to fall or not; in the case of a single disturbance, the method was able to predict the fall just within a single step after the disturbance. In addition, the method has an advantage of low implementation complexity and a low number of test runs.

Hobbelen et al. introduced Limit Cycle Walking paradigm for a bipedal locomotion with a Gait Sensitivity Norm as new disturbance rejection measure, which can be used as a robust fall indicator [13].

Kanoi and Hartland [14] investigated a use of Reservoir Computing for meta-sensor conception, involving generation of temporal meta-sensor for fall detection that was based on actual robot sensors. Their model was able to provide insight into robot status in the context of fall detections together with a low error rate. The model can be applied online and shown to be accurate in detecting instabilities that lead to robot falls.

Höhn and Gerth [15] proposed a probability-based balance monitoring concept with two algorithms that allows distinguishing between normal operation and instability. First algorithm uses Gaussian-Mixture Models (GMM) to describe the distribution of the robot's sensor data for two different states - stable locomotion or falling. Using this model and incoming sensory data it is possible to estimate the probability of the robot being in one of these states. The second algorithm is based on Hidden-Markov-Models (HMM), and the model is utilized in order to detect and identify unstable states using estimated parameters of their typical sequences in the robot's sensor data. Learning phase needed for estimation distribution densities and HMM parameters are generated with help of a simulation program. Robustness of the algorithms was tested in simulated experiments. The feature vectors of model were sampled every 10 ms within experiments. GMM and HMM algorithms took less than a millisecond on a desktop PC, that was also simulating the dynamical model of the robot. Hence, an online operation on the robot's microcontroller is feasible.

Goswami and Kalyanakrishnan introduced a system that uses supervised machine learning approach to achieve reliable fall prediction [20]. Learned solutions were combined into decision lists within 16-dimensional feature space, and the false positive rate and lead-time tradeoff could be further controlled with internal parameters adjustment. Simulation of ASIMO-like robot were performed in order to verify the proposed solution.

Jeong-Jung Kim et al. proposed a state classification method for detecting falling with Support Vector machine (SVM) to classify the state [22]. SVM utilized sensor data of robot accelerometer and force sensing resistor (FSR) sensor. Training of the classifier was performed off-line and the trained classifier is used to classify the state of the biped robot in on-line mode. Robot simulator was used to verify the method. This approach was able to classify falling state within 0.01 s.

Hofmann et al. proposed a fall protection system based on an artificial MLP neural network using a time series of gyroscope values [21]. Experiments were performed with a low cost small-size robotic platform NAO, which unfortunately could not be immediately scaled up for human-size robots.

3 Fall Management

There are two primary objectives of dealing with the robot accidental fall over: (a) minimizing damage to the robot and (b) minimizing damage to objects in the vicinity of the fall. Strategy of reducing damage of the impact is primary when the robot is operating in a free space. On the contrary, in situations when the falling robot can cause injury to a person or damage to objects in its vicinity, the primary objective should be to eliminate such possibility.

While most researches treat fall as an unavoidable part of bipedal walking and focus on developing strategies to avoid falls and to minimize mechanical damage Wilken et al. [16] have investigated a deliberate fall of a humanoid soccer goalkeeper. Although their strategy to minimize fall damage consists mostly of mechanical solutions and concentrates on joints relaxation just before ground impact.

Another approach of fall damage minimizing utilizes heuristics such as manipulating a center of mass (CoM) of a robot. Ruiz-del Solar et al. [17] investigated several strategies, which were inherited from Japanese martial arts and are to be applied in the direction of a fall; each strategy concentrated on lowering the robot CoM. Each falling strategy produced a sequence of motions that modified the geometry of the robot body with intent to decrease the force of the impact, and spreading kinetic energy of the fall to transfer through a broader contact area. Based upon this research they implemented a low damage fall strategies for robots playing soccer [18].

Ishida et al. performed analysis of SDR-4X II robot fall, mimicking shock absorbers with servos using servo loop gain shift [19].

Fujiwara et al. in their comprehensive work with human-size HRP-2 robot, presented their solutions for fall management in a series of publications [2–4]. They presented “UKEMI” strategy, a falling motion control that minimizes damage to a humanoid robot. This strategy employs optimal falling maneuvers to minimize impact force and angular momentum. To minimize the landing impact of a falling motion, they use optimization technique based on variations calculation with a quadruple inverted pendulum model that was used to represent a falling motion. They tested the estimated optimal forward falling motion and obtained a smooth and damage-free fall [3]. Main drawback of the method is that it is based on an off-line optimization and does not support a real-time motion generation for humanoid robots in real environment. To conduct more experiments of falling over motion of HRP OpenHRP dynamics simulator was utilized [2]. With simulation, they obtained good estimates of robot states that are difficult to measure directly on a real robot, such as forces and moments acting on the hip joint, while robot does not have a six-axis force sensor at the hip. This knowledge is very important in order to design proper hip joint structure, which arguably is the most complex structure of a humanoid robot. Comparison with experimental results of a real humanoid robot demonstrated that an overall behavior of the robot simulated falling motion corresponds well with real experiments. Further experiments indicated that the impact force could be damped effectively even if the shock-absorbing features does not present in entire body of the robot. To decrease damages further, they have studied a balance between landing impact force and a position as well as the stability after landing and the position. Adding braking after the CoM lowering by extending the body just before the impact with the ground reduced the impact velocity. In order to make joints more compliant, the feedback gain reduction after braking was introduced [4].

Ogata et al. analyzed trajectories of CoM, both straight [11] and curvilinear [10]. Thus was performed for both phases of lowering the CoM and extending the body for reduction of the vertical impact speed.

Ruiz-del Solar et al., instead of minimizing the ground impact velocity, sought minimization of axial force and torque induced by the impact [17]. Using motion-capture data, a fall was analyzed and a human operator changed the joints positions to reduce the impact over the joints with maximal impulses.

In their study of intentional fall, Wilken et al. adopted an inverse approach. Instead of minimizing the fall damage, they first designed the fall motions and then changed the robot's structure to reduce the damage. Springs and flexible rubber struts were added to the most damage-prone locations of the robot was given the deliberate fall motion of a robot soccer goalkeeper [16].

Goswami et al. studied a control strategy for changing a default fall direction of a robot so that it could avoid collisions with surrounding people or objects in order to minimize damage to others. This strategy used the fact that the robot falling definitely happens at an edge of its support. The authors modified the position and orientation of this edge to change the fall trajectory to suit the environment. As the fall is predicted controller infers the optimal trajectory, which results in the safest fall. The fall controller was also enhanced with inertia shaping that changes robot's centroidal axis inertia [19].

Seung-kook Yun et al. proposed another approach to reduce damage to a humanoid robot during a fall [23]. Instead of finding an optimal configuration of the falling down robot, this strategy seeks to stop the robot from falling all the way to the ground, preventing full conversion of the robot's potential energy into kinetic energy, thus minimizing the force of impact. This is achieved via a sequence of three contacts with the ground of the swing foot and two hands. The final configuration resembles a tripod as it has a stable three-point contact with the ground with the robot's CoM above the ground.

Vincent Samy et al. proposed a fall strategy that combines two behaviors. The first behavior involves a closed-loop pose correction during the falling process, which would help to achieve best impact absorption. The second behavior performs a servo active compliance mode through instant PD gains reduction, instead of shutting-down or high-gains control. The authors suggested utilizing actuators as a spring-damper system by analyzing velocity, computing effective mass at the link's contact points and the motors characteristics [24].

Sehoon Ha et al. suggested another approach, which deals with planning of fall contact points in order to effectively dissipate momentum [25]. Given an unstable initial position, the planner searches for an optimal sequence of contact points such that the initial momentum is dissipated with minimal impacts. Rather than choosing from a collection of individual control strategies, the proposed method is a generic algorithm, which plans for appropriate maneuvers. Algorithm estimates the number of contacts, the order of contacts, and the position and time of contacts for supporting further momentum dissipation with a minimal damage to the robot.

A fall prevention system developed by Park et al. [30] used an inertial-measurement unit (IMU) to detect if the robot is falling or not. In the case of falling, the robot performed a forward step with a swing leg in order to prevent falling. Yet, the approach was tested in simulation experiments only.

4 Future Work: Fall Detection and Prevention for AR-601

The presented above algorithms are carefully tailored and verified in simulations and/or experimental work by their authors to support particular models of small-size or human-size robots. Practical implementation of each algorithms is not transferable to other models due to different hardware specifications and configuration, and, to the best of our knowledge, a generic solution does not exist yet. We avoid declaring an ambitious goal of suggesting such generic solution, but are interested to perform applied research on developing algorithms of fall detection and fall prevention that would maintain static and dynamic stability of our human-size robot AR-601.

Our target platform is bipedal robot AR-601 with 41 active degrees of freedom (DoF) that have been developed by Russian company "Android Technics" (Fig. 1, left). The total mass of the robot is 65 kg, the height is 1442 mm. Mass, and size parameters of the robot legs are given in Table 1, and for further hardware details about AR-601 the interested reader could refer to [31]. We had presented a virtual model of the robot in Matlab/Simulink environment together with a corresponding model in ROS/Gazebo environment (Fig. 1, right). These models were applied for modeling and algorithm evaluation, which utilized mass characteristics of the real robot, such as mass, CoM location and moments of inertia for each part. Locomotion control during the robot locomotion uses only 12 leg joints (6 DoF in each leg) driven by small electric motors with STM32F103T8U6 controllers and the communication protocol provides information about all motor states, pressure in robot's feet and on-board gyroscopes. Each leg consists of three joint axes in the hip, two joints in the ankle and one in the knee. We had modeled and experimentally verified dynamically stable AR-601 M robot locomotion with VHIPM and preview control methods [26].

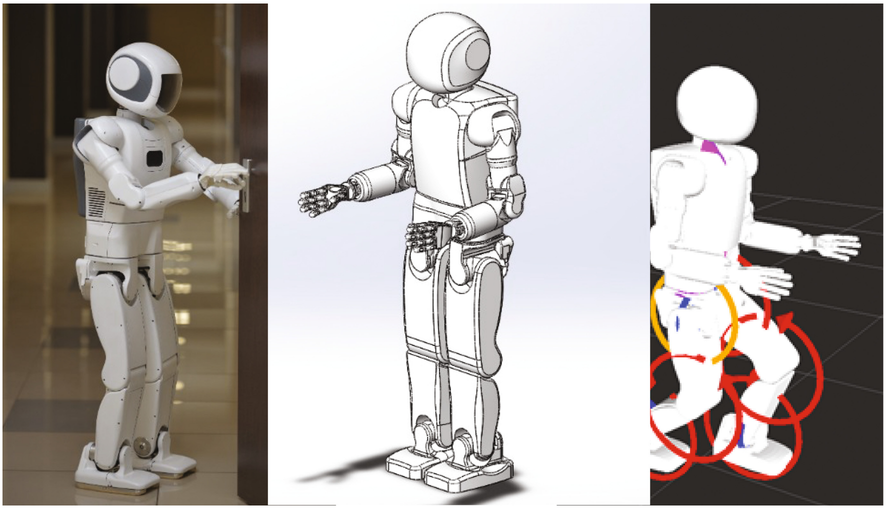

Fig. 1. Anthropomorphic robot AR-601 (left), its model in Solidworks (center) and ROS gazebo environment (right)

Table 1. Mass and size parameters of AR-601 legs

Link	Size parameters (mm)	Mass (kg)
Thigh	Length : 280	7.5
Shank	Length: 280	6.9
Foot	L × W × H: 254 × 160 × 106	3.2

During simulation in Matlab/Simulink and ROS/Gazebo environments that were followed by locomotion experiments, we encountered multiple instabilities that resulted in robot falls. These problems were persistent and required significant efforts during demonstrations in order to consistently preserve the robot, surrounding people and environment. To deal with this issue we acknowledge the acute need of diving into the field of fall detection and management. Using our model in virtual environment, we plan to test aforementioned algorithms to manage such situations.

5 Conclusions

In this paper we discussed different approaches to fall detection and management procedures for humanoid robots of small-size and human-size, which were verified in simulations and experimental work. Fall detection procedures are primarily based on various classification algorithms using supervised learning. For fall management, many approaches are centered on dissipating initial momentum of the fall using posture control. Another popular trend in fall management suggests using actuators to simulate shock absorbers.

We presented a brief overview of Russian bipedal robot AR-601, its modelling and simulation in Matlab/Simulink and ROS/Gazebo environments. Our future work concentrates on implementing fall detection and management procedures and verifying their performance for AR-601, both in intensive simulations and experiments.

Humanoid robot domain is not the only field, which deals with fall detection and management; these issues go far beyond robotics field and are important particularly in geriatric medicine. As a part of our long-term future work, we are interested to employ our insights on fall management in order to adapt humanoid robot algorithms for elderly support devices in order to improve their safety and quality of life.

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References

1. Goswami, A., Yun, S.K., Nagarajan, U., Lee, S.H., Yin, K., Kalyanakrishnan, S.: Direction-changing fall control of humanoid robots: theory and experiments. Auton. Robots **36**(3), 199–223 (2014)
2. Fujiwara, K., Kanehiro, F., Saito, H., Kajita, S., Harada, K., Hirukawa, H.: Falling motion control of a humanoid robot trained by virtual supplementary tests. In: IEEE International Conference on Robotics and Automation Proceedings, ICRA 2004, vol. 2, pp. 1077–1082, April 2004
3. Fujiwara, K., Kajita, S., Harada, K., Kaneko, K., Morisawa, M., Kanehiro, F., Hirukawa, H.: Towards an optimal falling motion for a humanoid robot. In: 2006 6th IEEE-RAS International Conference on Humanoid Robots, pp. 524–529, February 2007
4. Fujiwara, K., Kajita, S., Harada, K., Kaneko, K., Morisawa, M., Kanehiro, F., Hirukawa, H:. An optimal planning of falling motions of a humanoid robot. In: IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2007, pp. 456–462, October 2007
5. Chia, P.C., Lee, C.H., Chen, T.S., Kuo, C.H., Lee, M.Y., Chen, C.M.S.: Correlations of falling signals between biped robots and humans with 3-axis accelerometers. In: International Conference on System Science and Engineering (ICSSE), pp. 509–514, June 2011
6. Forner Cordero, A.: Human Gait, Stumble and… fall? Mechanical limitations of the recovery from a stumble. Universiteit Twente (2003)
7. Cordero, A.F., Koopman, H.F.J.M., Van der Helm, F.C.T.: Multiple-step strategies to recover from stumbling perturbations. Gait Posture **18**(1), 47–59 (2003)
8. Cordero, A.F., Koopman, H.J.F.M., van der Helm, F.C.: Mechanical model of the recovery from stumbling. Biol. Cybern. **91**(4), 212–220 (2004)
9. Renner, R., Behnke, S.: Instability detection and fall avoidance for a humanoid using attitude sensors and reflexes. In: IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 2967–2973, October 2006
10. Ogata, K., Terada, K., Kuniyoshi, Y.: Real-time selection and generation of fall damage reduction actions for humanoid robots. In: 8th IEEE-RAS International Conference on Humanoid Robots, Humanoids, pp. 233–238, December 2008

11. Ogata, K., Terada, K., Kuniyoshi, Y.: Falling motion control for humanoid robots while walking. In: 7th IEEE-RAS International Conference on Humanoid Robots, pp. 306–311, November 2007
12. Karssen, J.D., Wisse, M.: Fall detection in walking robots by multi-way principal component analysis. Robotica **27**(02), 249–257 (2009)
13. Hobbelen, D.G., Wisse, M.: A disturbance rejection measure for limit cycle walkers: the gait sensitivity norm. IEEE Trans. Robotics **23**(6), 1213–1224 (2007)
14. Kanoi, R., Hartland, C.: Fall detections in humanoid walk patterns using reservoir computing based control architecture. In: 5th National Conference on Control Architecture of Robots, May 2010
15. Höhn, O., Gerth, W.: Probabilistic balance monitoring for bipedal robots. Int. J. Robotics Res. **28**(2), 245–256 (2009)
16. Wilken, T., Missura, M., Behnke, S.: Designing falling motions for a humanoid soccer goalie. In: International Conference on Humanoid Robots Proceedings of the 4th Workshop on Humanoid Soccer Robots (2009)
17. Ruiz-del-Solar, J., Moya, J., Parra-Tsunekawa, I.: Fall detection and management in biped humanoid robots. In: 2010 IEEE International Conference on Robotics and Automation (ICRA), pp. 3323–3328, May 2010
18. Ruiz-del-Solar, J., Palma-Amestoy, R., Marchant, R., Parra-Tsunekawa, I., Zegers, P.: Learning to fall: designing low damage fall sequences for humanoid soccer robots. Robotics Auton. Syst. **57**(8), 796–807 (2009)
19. Nagarajan, U., Goswami, A.: Generalized direction changing fall control of humanoid robots among multiple objects. In: 2010 IEEE International Conference on Robotics and Automation (ICRA), pp. 3316–3322, May 2010
20. Kalyanakrishnan, S., Goswami, A.: Learning to predict humanoid fall. Int. J. Humanoid Robotics **8**(02), 245–273 (2011)
21. Hofmann, M., Schwarz, I., Urbann, O., Ziegler, F.: A Fall Prediction System for Humanoid Robots Using a Multi-Layer Perceptron
22. Kim, J.J., Choi, T.Y., Lee, J.J.: Falling avoidance of biped robot using state classification. In: IEEE International Conference on Mechatronics and Automation, ICMA 2008, pp. 72–76, August 2008
23. Yun, S.K., Goswami, A.: Tripod fall: concept and experiments of a novel approach to humanoid robot fall damage reduction. In: 2014 IEEE International Conference on Robotics and Automation (ICRA), pp. 2799–2805, May 2014
24. Samy, V., Kheddar, A.: Falls control using posture reshaping and active compliance. In: 2015 IEEE-RAS 15th International Conference on Humanoid Robots (Humanoids), pp. 908–913, November 2015
25. Ha, S., Liu, C.K.: Multiple contact planning for minimizing damage of humanoid falls. In: 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 2761–2767, September 2015
26. Khusainov, R., Afanasyev, I., Sabirova, L., Magid, E.: Bipedal robot locomotion modelling with virtual height inverted pendulum and preview control approaches in Simulink environment. J. Robotics Netw. Artif. Life **3**(3), 182–187 (2016)
27. Wright, J., Jordanov, I.: Intelligent approaches in locomotion. In: The 2012 International Joint Conference on Neural Networks (IJCNN), pp. 1–8, June 2012
28. Hurmuzlu, Y., Génot, F., Brogliato, B.: Modeling, stability and control of biped robots—a general framework. Automatica **40**(10), 1647–1664 (2004)
29. Asano, F., Luo, Z.W.: Energy-efficient and high-speed dynamic biped locomotion based on principle of parametric excitation. IEEE Trans. Robotics **24**(6), 1289–1301 (2008)

30. Park, G.-M., Baek, S.-H., Kim, J.-H.: Falling prevention system from external disturbances for humanoid robots. In: Kim, J.-H., Yang, W., Jo, J., Sincak, P., Myung, H. (eds.) Robot Intelligence Technology and Applications 3. AISC, vol. 345, pp. 97–105. Springer, Cham (2015). doi:10.1007/978-3-319-16841-8_10
31. Khusainov, R., Shimchik, I., Afanasyev, I., Magid, E.: 3D modelling of biped robot locomotion with walking primitives approach in Simulink environment. In: Filipe, J., Madani, K., Gusikhin, O., Sasiadek, J. (eds.) Informatics in Control, Automation and Robotics 12th International Conference, ICINCO 2015 Colmar, France, July 21-23, 2015 Revised Selected Papers. LNEE, vol. 383, pp. 287–304. Springer, Cham (2016). doi:10.1007/978-3-319-31898-1_16