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Dynamic Heel-Strike Toe-Off Walking Controller for Full-Size Modular Humanoid Robots

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Abstract— **General purpose modular actuators have greatly lowered the difficulty of building and maintaining high degree of freedom humanoid robots. In addition to widely adopted miniature modular humanoid robots, full-size humanoid robots can now be built using such modular actuators. To overcome torque and control bandwidth limitations of modular actuators, such robots tend to have a design principle of relatively short leg length and large foot size. However, the kinematic constraints from such design limit the bipedal mobility of the robot. In this paper, we present an efficient walking controller that utilizes a moving Zero Moment Point (ZMP) trajectory, automatically calculated heel and toe lift motions and a reference foot tilt trajectory to generate a dynamic heel-strike toe-off gait with large stride lengths while overcoming the kinematic constraints. We demonstrate the suggested controller in physically realistic simulations, and on the THOR-RD full-sized humanoid robot.**

Keywords: modular actuator, full-size humanoid robot, kinematic constraint, heel and toe lift, heel-strike toe-off walk

I. Introduction

Thanks to the introduction of commercial miniature humanoid robots [1], [2] and the popularity of the humanoid robotic competitions, an increasing number of researchers now have access to physical humanoid robot platforms. The availability of commercial off-the-shelf modular actuators has also made the task of building custom humanoid robot significantly easier [3], [4], and now it is possible to build a full-size, general purpose humanoid robot with modular actuators [5], [6].

However, due to various limitations such as housing size, heat dissipation and control bus structure, general purpose modular actuators tend to have slower control frequency and lower maximum torque compared to custom actuators. To ensure the stability of modular humanoid robots under such limitations, they share a common design approach; relatively short legs that lowers the center of mass (COM) height and joint torque requirements, and large feet that provides increased static stability. One big downside of such a design is limited bipedal mobility of the robot, as short legs limit the maximum stride length, yet larger feet require larger strides to handle obstacles.

On the other hand, it is well known that humans use quite different gait patterns compared to typical bipedal robot gait, which keeps the knee bent and feet parallel to the ground. Humans walk with knees almost fully extended, and heel lands the ground first and toe leaves off the ground last. There have been a number of researches in robotics field that aim to realize this heel-strike toe-off gait on humanoid robots [7], [8], [9]. Many of them focus on the human-likeness and energy-efficiency of such a walk motion [10], but some researchers have also focused on increasing the stride length for higher walk velocity on flat surfaces [11], [12], [13]. In our previous work , we have used the heel and toe lift motions to increase the leg reach for quasi-static walk over uneven terrain [14].

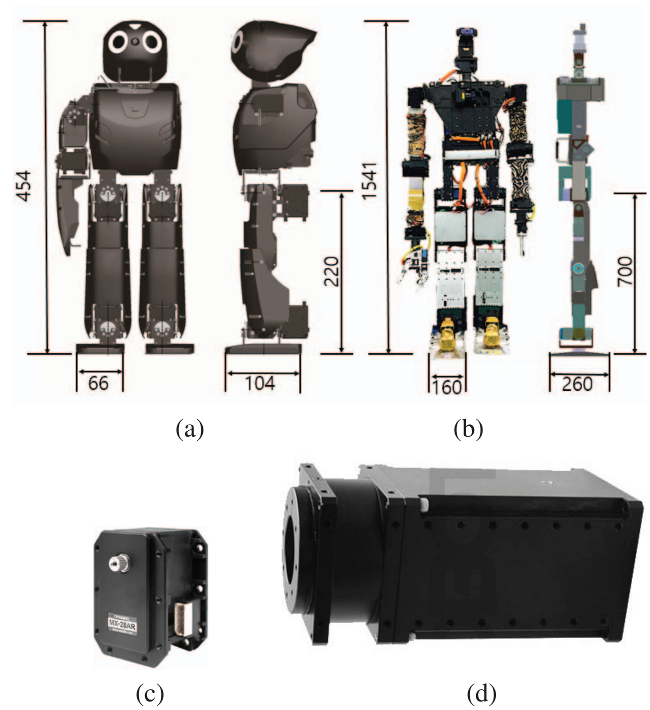

Fig. 1. DARwIn-OP and THOR-RD modular humanoid robots and their modular actuators. (a) DARwIn-OP miniauture humamanoid robot and its dimensions. (b) THOR-RD full-size humamanoid robot and its dimensions. (c) The MX-28 modular actuator used for the DARwIn-OP robot. (d) The H54-200 modular actuator used for the THOR-RD robot.

In this work, we extend our previous walking controller that uses automatic heel and toe lift motion for a dynamic walking over flat surface with large stride lengths. In addition to the automatic heel and toe lift that keeps feet edge on target surface while satisfying kinematic and joint range of motion constraints, a reference foot tilt angle trajectory is used to generate a more natural heel-strike toe-off gait, and the torso trajectory is generated from a reference ZMP trajectory that moves from heel to toe of each foot. We validate our approach in physically realistic simulations, as well as using the THOR-RD full-sized humanoid robot.

The remainder of the paper proceeds as follows. Section

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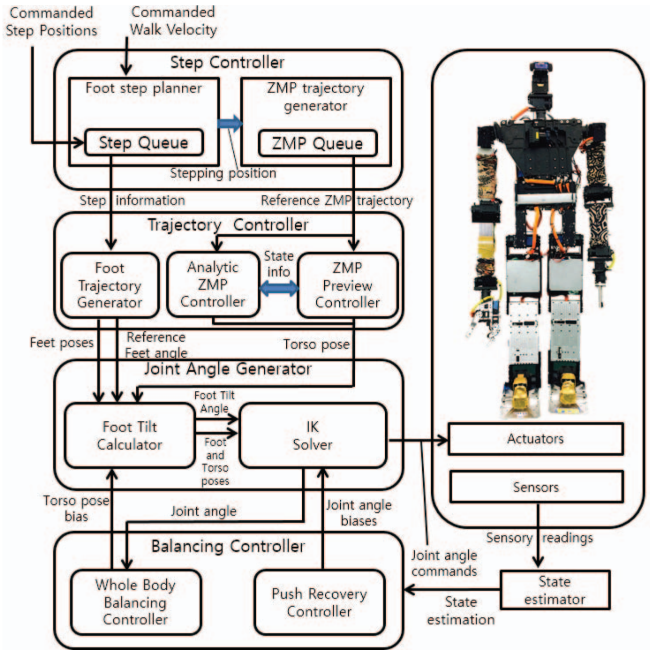


Fig. 2. The overall structure of the motion controller.

II describes the outline of the control architecture and gives a brief introduction of each component. Section III explains how each component is extended to support the dynamic heel-strike toe-off walking. Sections IV and V show results using a physics-based simulation and experiments using physical humanoid robots. Finally, we conclude with a discussion of potential future directions arising from this work.

II. Outline of the Control Structure

Figure 2 shows the overview of the motion control architecture used in this paper, which is extended version of [14] to support the moving ZMP trajectory required for dynamic heel-strike toe-off walking. It has four main components. The step controller uses the user imput to generate the future step locations and corresponding ZMP trajectories. The trajectory controller generates reference feet and torso trajectories based on a simplified dynamics model. The joint angle generator generates joint angles to satisfy kinematic constraints of the robot utilizing heel and toe tilt. The balancing controller handles whole body balancing and reactive push recovery. We will cover each controller in more detail in the following section.

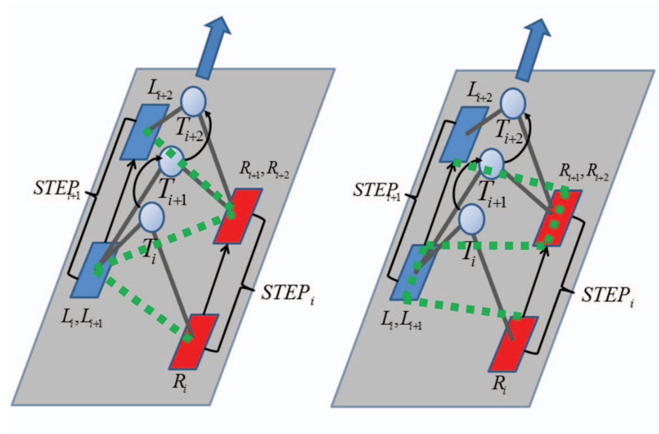
III. Heel-Strike Toe-Off Walking Controller

In this section, we will review each controller and present how each controllers are extended to handle the dynamic heel-strike toe-off walking.

A. Step Controller

Step controller receives the commanded walk velocity or commanded foot step positions to generate a number of future steps, where each step is defined as

$$STEP_i = \{SF, WT, t_{STEP}, L_i, T_i, R_i, L_{1+1}, T_{i+1}, R_{i+1}\} \quad (1)$$



(a) (b)

Fig. 3. Step definitions and the corresponding ZMP trajectory, shown as green dotted lines. (a) stationary ZMP (b) moving ZMP

where SF denotes the support foot, WT denotes the type of the step, t_{STEP} is the duration of the step, and L_i, T_i, R_i, and $L_{i+1}, T_{i+1}, R_{i+1}$ are the initial and final 6D poses of left foot, torso and right foot in $(x, y, z, \alpha, \beta, \gamma)$ coordinates. Once the step parameters are determined, the reference ZMP trajectory $p_i(\phi)$ is calculated as a piecewise linear function of walk phase ϕ. To handle a dynamic heel-strike toe-off gait, we use a moving ZMP trajectory that linearly moves from the heel to the toe of each foot during single support phase as following

$$p_i(\phi) = \begin{cases} T_i \frac{\phi_1 - \phi}{\phi_1} & + \quad L_i^{HEEL} \frac{\phi}{\phi_1} & 0 \le \phi < \phi_1 \\ L_i^{TOE} \frac{\phi - \phi_1}{\phi_2 - \phi_1} & + \quad L_i^{HEEL} \frac{\phi_2 - \phi}{\phi_2 - \phi_1} & \phi_1 \le \phi < \phi_2 \\ T_{i+1} \frac{\phi - \phi_2}{1 - \phi_2} & + \quad L_i^{TOE} \frac{1 - \phi}{1 - \phi_2} & \phi_2 \le \phi < 1 \end{cases} \quad (2)$$

for the left support case, where L_i^{TOE} and L_i^{HEEL} are the heel and toe poses of left foot. Figure 3 shows the step definitions and the corresponding ZMP trajectory during heel-strike toe-off walking.

B. Torso Trajectory Generation

Once the reference ZMP trajectory is generated, the reference torso trajectory is then calculated using our hybrid walking controller that can dynamically switch between the ZMP preview controller and analytic controller while movement [15]. The ZMP preview controller can straightforwardly accept moving ZMP trajectory of (2), but the analytic controller need to be updated. We use a simple approach of interpolating two closed form solutions for stationary ZMP

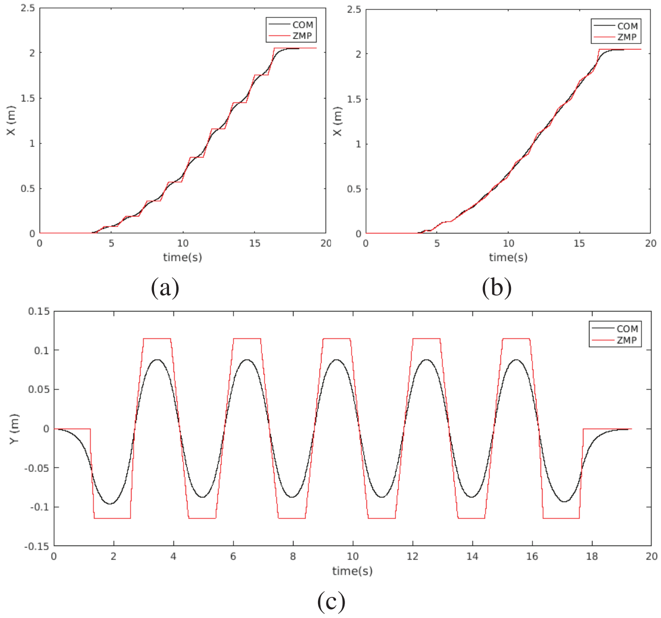


Fig. 4. The ZMP and COM trajectory from stationary and moving reference ZMP trajectories. (a) X axis, stationary ZMP (b) X axis, moving ZMP (c) Y axis

trajectories as

$$x_i(\phi) = p_i(\phi) + \begin{cases} a_i^{pH} e^{\phi/\phi_{ZMP}} \\ + a_i^{nH} e^{-\phi/\phi_{ZMP}} \\ + m_i t_{ZMP} \frac{\phi-\phi_1}{\phi_{ZMP}} \\ - m_i t_{ZMP} \sinh \frac{\phi-\phi_1}{\phi_{ZMP}} & 0 \le \phi < \phi_1 \\[2ex] \frac{\phi_2-\phi}{\phi_2-\phi_1} a_i^{pH} e^{\phi/\phi_{ZMP}} \\ + \frac{\phi_2-\phi}{\phi_2-\phi_1} a_i^{nH} e^{-\phi/\phi_{ZMP}} \\ + \frac{\phi-\phi_1}{\phi_2-\phi_1} a_i^{pT} e^{\phi/\phi_{ZMP}} \\ + \frac{\phi-\phi_1}{\phi_2-\phi_1} a_i^{nT} e^{-\phi/\phi_{ZMP}} & \phi_1 \le \phi < \phi_2 \\[2ex] a_i^{pT} e^{\phi/\phi_{ZMP}} \\ + a_i^{nT} e^{-\phi/\phi_{ZMP}} \\ + n_i t_{ZMP} \frac{\phi-\phi_2}{\phi_{ZMP}} \\ - n_i t_{ZMP} \sinh \frac{\phi-\phi_2}{\phi_{ZMP}}) & \phi_2 \le \phi < 1 \end{cases} \tag{3}$$

$$m_i = (L_i^{HEEL} - C_i)/\phi_1$$
$$n_i = -(L_i^{TOE} - C_{i+1})/(1-\phi_2)$$

where $\phi_{ZMP} = t_{ZMP}/t_{STEP}$ and t_{ZMP} is the natural period of the inverted pendulum, and the parameters a_i^{pH}, a_i^{nH}, a_i^{pT}, a_i^{nT} can be uniquely determined by the boundary conditions. Figure 4 shows the resulting x and y axis COM trajectories for stationary and moving ZMP trajectories.

C. Foot Trajectory Generation

Given the initial and final swing foot poses, the swing foot trajectory in 3D Cartesian space is generated using predefined foot trajectory functions. We use square shaped trajectory function for rough terrain traversal to maximize the foot clearance from the terrain, and cycloid shaped trajectory function for flat terrain. In addition to the 3D foot trajectory, we include the additional reference foot tilt trajectory to generate a more natural heel-strike toe-off gait, which is explained in more detail in the next subsection.

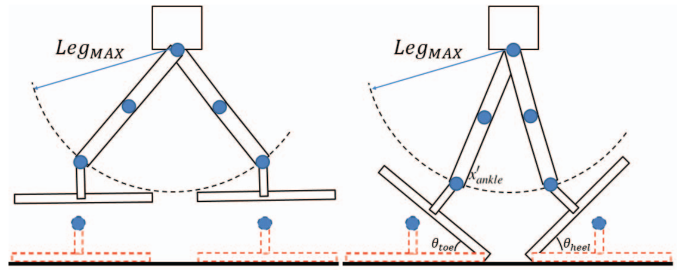


Fig. 5. Automatic calculation of the desired heel and toe tilt ankle

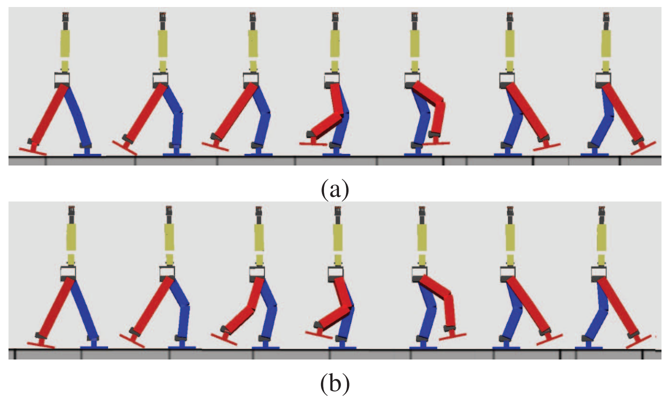
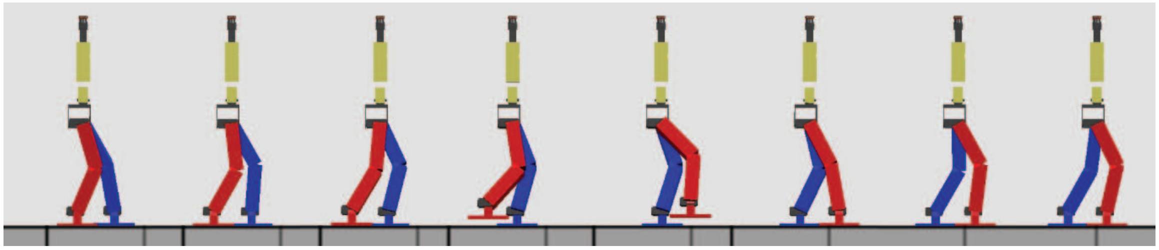


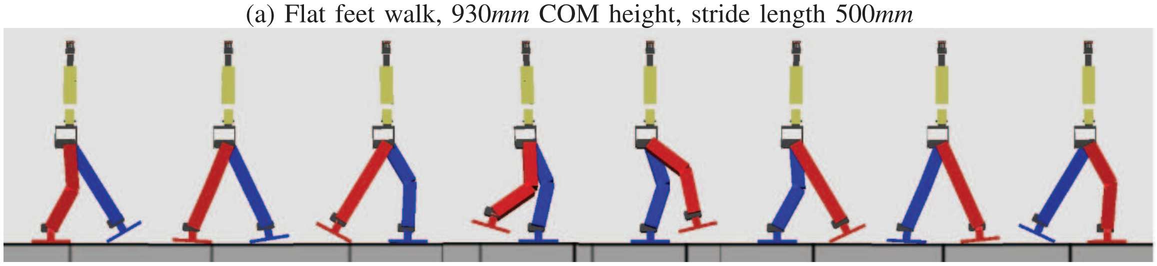
Fig. 6. Comparison of gaits with and without additional reference foot tilt trajectory. (a) Gait without reference foot tilt trajectory (b) Gait with reference foot tilt trajectory

D. Joint Angle Generation

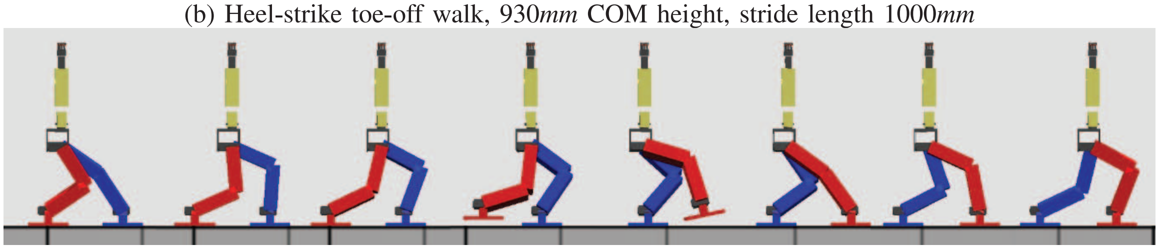
The generated torso and feet trajectories do not consider the kinematic constraints of the robot, and will not be realizable if the target feet poses are beyond the reach of the robot legs. However, humans can achieve large stride by utilizing heel and toe tilt motions. In our previous work, we present a walking controller that automatically generates heel and toe tilt motion to keep both feet on the ground while satisfying kinematic constraint during quasi-static walking [14]. We utilize the controller for dynamic walking case so that each feet keeps the target position and ground clearance while satisfying the kinematic constraint, as shown in Figure 5. Although the automatically generated heel and toe tilt motion can generate heel-strike and toe-off behavior without specifying the foot tilt angle, the resulting gait will keep the swing foot parallel to the ground unless the knee is fully extended. To generate a more natural heel-strike toe-off gait while maintaining foot clearance from the ground, we use the optional reference foot tilt trajectory that determines the minimum foot tilt angle for the each phase of the gait. Figure 6 shows the comparison of gaits with and without reference foot tilt trajectory, where a simple sine function is used for the reference foot tilt trajectory.



(a) Flat feet walk, 930mm COM height, stride length 500mm



(b) Heel-strike toe-off walk, 930mm COM height, stride length 1000mm



(c) Flat feet walk with 790mm COM height, stride length 1000mm

Fig. 7. THOR-RD robot walkig in simulated environment.

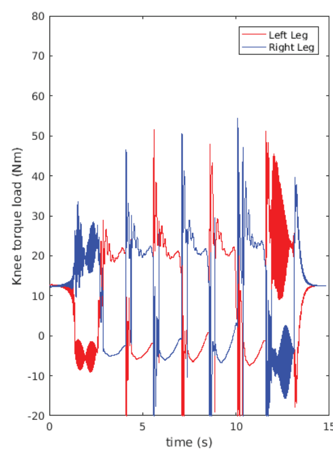
IV. Simulation Results

We have first tested the suggested walk controller in a simulated environment using simulated model of the THOR-RD full-size modular humanoid robot. For simulation, the Webots [16] commercial robotics simulator using the Open Dynamics Engine (ODE) physics library has been used. The motion controller update frequency is set to 120 Hz, the same frequency as the actual robot, and the physics simulation time step is set to 1 ms. Ankle force torque sensors are not used, and only IMU values are used to stabilize the robot.

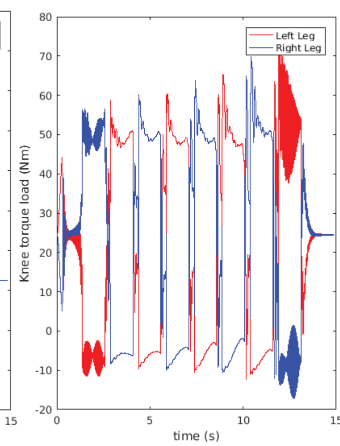
Figure 7 shows the THOR-RD robot in a simulated environment. With our default COM height of 930 mm and step timing $t_{STEP} = 0.8$ s, we have found the maximum achievable stride length with flat feet to be roughly 500 mm. On the other hand, we could achieve much larger stride length of 1000 mm utilizing the heel and toe tilt motion and moving reference ZMP trajectory. Further increasing the stride length makes the robot spend more time supported by just two feet edges, and eventually lose balance. For comparison, we test a lowered COM height and flat feet trajectory to achieve the same stride length as well, but it results in much higher knee load as shown in Figure 8, so is not reliably realizable with physical THOR-RD robot.

V. Experimental Results

We have implemented the suggested walk controller on the THOR-RD full-size humanoid robot, which is 154 cm tall, weighs 54 kg with two 7 degree of freedom arms and 41 kg with dummy arms. It has a 3.3 Ghz Intel Core i5 processor for the onboard processing, has various sensors including IMU, ankle force torque sensors and joint encoders at the joints. The force torque sensors are not used in this work, and only IMU readings are used for balancing.



(a)



(b)

Fig. 8. Comparison of knee torque load in simulated environment while walking with different walk patterns. (a) Heel-strike toe-off walk, 930mm COM height, stride length 1000mm (b) Flat feet walk, 790mm COM height, stride length 1000mm

We have used the suggested walking controller on the THOR-RD full-size humanoid robot at the RoboCup 2015 international robotic soccer competition, where the robot should walk autonomously over the field covered with 50 mm

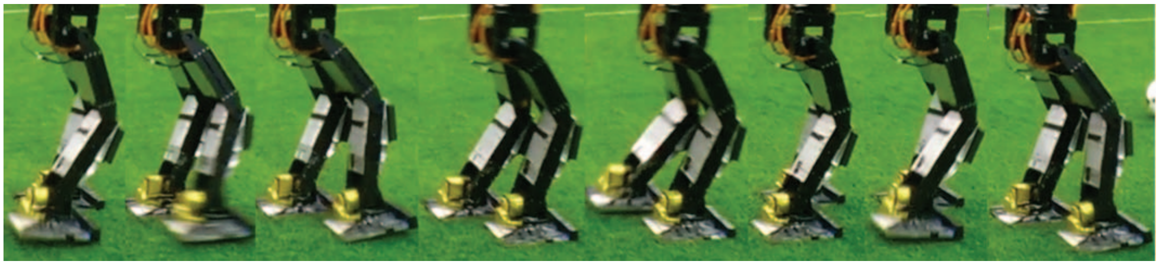


Fig. 9. THOR-RD robot doing a heel-strike toe-off walk on artificial grass

thick artificial grass. Step timing t_{STEP} is set as 0.8 s and the maximum stride length is set as 280 mm, which is achievable without foot tilt motion. But we have found that a flat foot trajectory tends to make the robot kick the ground and lose balance due to the soft surface. We have used the foot tilt trajectory to generate a heel-strike toe-off walk shown in Figure 6 (b), which helped the robot to reliably walk on soft terrain and eventually win the competition. Figure 9 shows the walk sequence of the THOR-RD robot on the artificial grass.

In addition, we have used the suggested controller to make larger strides on hard surface. Step timing of t_{STEP}=1.5 s is used this time to keep peak joint velocities low. In spite of structural compliance of the robot and lack of force torque feedback, the THOR-RD robot could take a big stride with 750 mm length, as shown in Figure 10. We have found that the THOR-RD robot can also perform a continuous dynamic heel-strike toe-off walking with stride length 550 mm, shown in Figure 11, which is roughly double of previous maximum stride length with flat feet. We think a better calibration of the robot and accounting for the velocity and torque limitations of the actuators will further improve the locomotion performance.

VI. CONCLUSIONS

In this work, we describe a walking controller for a bipedal humanoid robot that utilizes a moving ZMP trajectory, automatically calculated foot tilt motions and additional reference foot tilt trajectory to generate a natural looking dynamic heel-strike toe-off gait while overcoming the kinematic constraints. Our approach is implemented and demonstrated in physically realistic simulations and experimentally on the THOR-RD full-size humanoid robot. The experimental results show that our method can help the robot achieve larger stride length without lowering the COM height, as well as generating a human-like heel-strike toe-off gait with a reference foot tilt trajectory. Future work will include updating the dynamics model of the robot to account for the large momentum of swinging leg to further improve the stability and performance of the locomotion.

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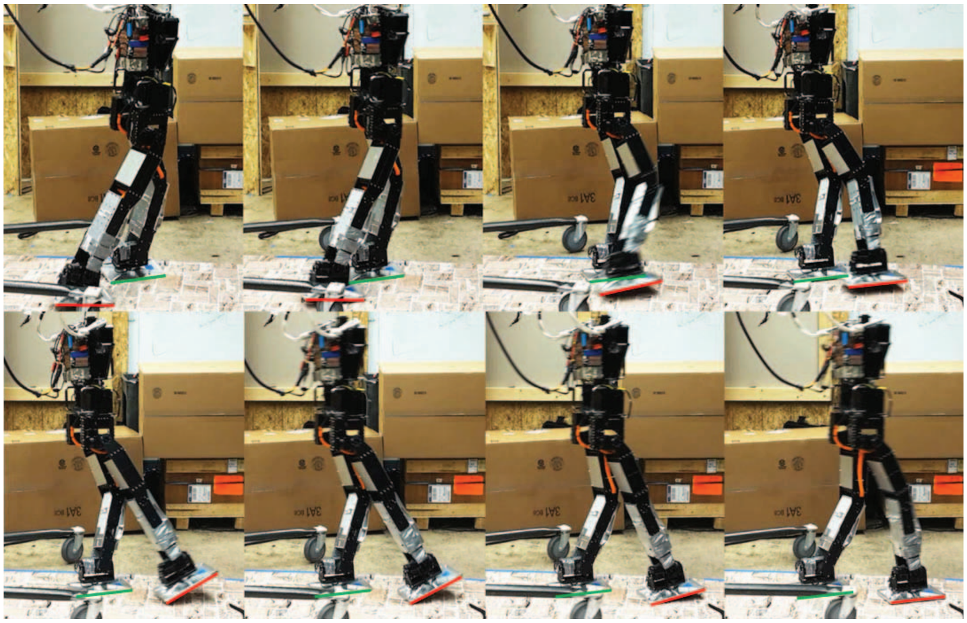

Fig. 10. THOR-RD robot taking a step with 750mm stride length using heel-strike toe-off motion. Foot edges are highlighted for better visibility.

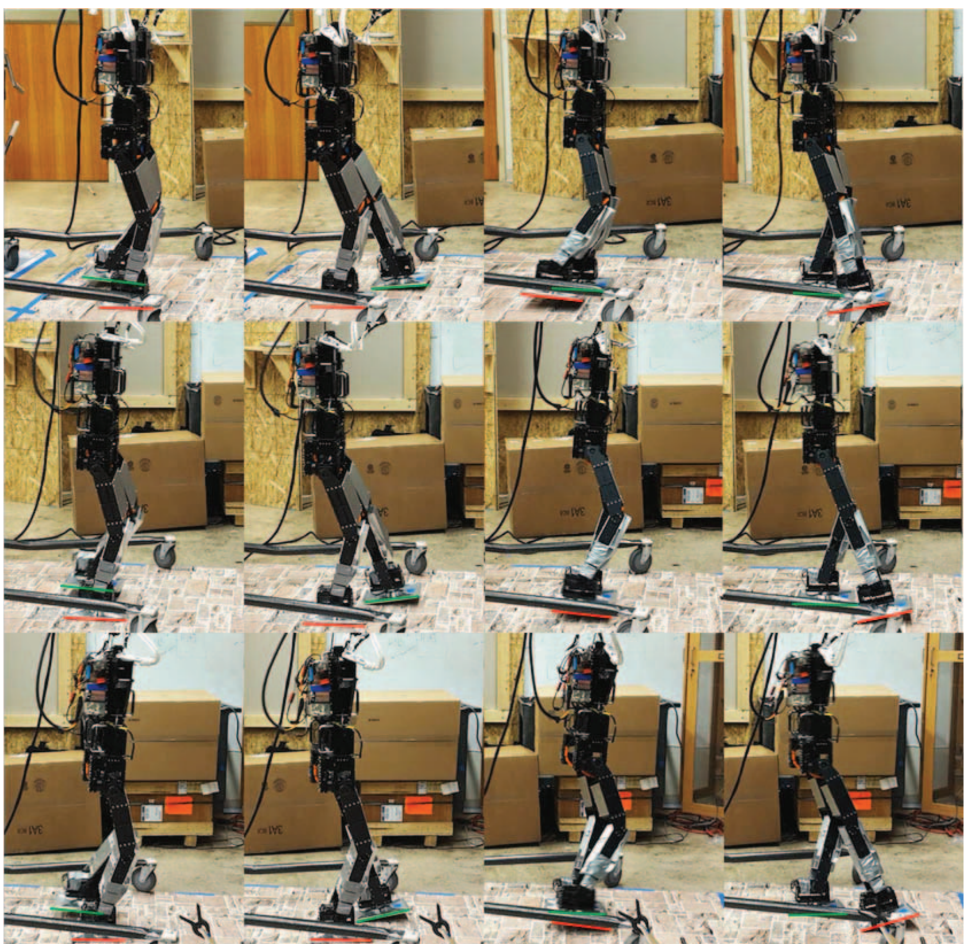

Fig. 11. THOR-RD robot doing a heel-strike toe-off walk with 550mm stride length on a flat surface. Foot edges are highlighted for better visibility.