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Walk and Kick Motion Generation for a General Purpose Full Sized Humanoid Robot

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***Abstract*— In this paper, we describe our adoption of the THOR-OP (Tactical Hazardous Operations Robot - Open Platform) full sized humanoid robot, originally developed to compete at the DARPA Robotics Challenge, for the RoboCup robotic soccer competition. For full sized general purpose humanoid robots, the zero moment point (ZMP) preview controller is widely used since it provides excellent stability and accepts generic walk patterns as inputs. However, simple reactive walk controllers can be advantageous in robot soccer applications that require limited onboard computation and handling of dynamic environment. We use a hybrid walk controller that dynamically switches between the reactive and preview ZMP controllers in order to leverage the best of both controllers. Reactive controllers are used to move the robot with little latency, and the preview controller is used for double support transition and dynamic kick generation. To make smooth transitions between these two controllers, the preview controller considers the boundary conditions of the center of mass (COM) state based on the analytic solution of the linear inverted pendulum model in its optimization process. The suggested controller is validated using the THOR-OP humanoid platform.**

Keywords: general purpose full sized humanoid robot, hybrid walk controller, dynamic kick generation

I. Introduction

Soccer playing humanoid robots represent some of the most advanced research in the field of humanoid robotics. Cutting edge abilities include unsupervised autonomy, onboard power and computation, and software and hardware that is robust to unknown environmental disturbances. The skill-sets achieved in the framework of robot soccer push the boundaries for attaining human abilities outside of just soccer; however, it remains a challenge to incorporate hardware and software required to attain those abilities. This requires a humanoid robot that is both "full sized" – roughly with adult human characteristics – and "general purpose" – with enough power and dexterity to handle various tasks. Such humanoid robots have been accessible to few researchers. Developing and maintaining the highly complex, multi-DOF humanoid robot is not a simple task that can take a large amount of time and effort.

For such a full sized general purpose humanoid robot, the widely used zero moment point (ZMP) preview based walk controller utilizes a set of future foothold positions before planning an optimal center of mass (COM) trajectory that keeps the robot dynamically stable during the gait while

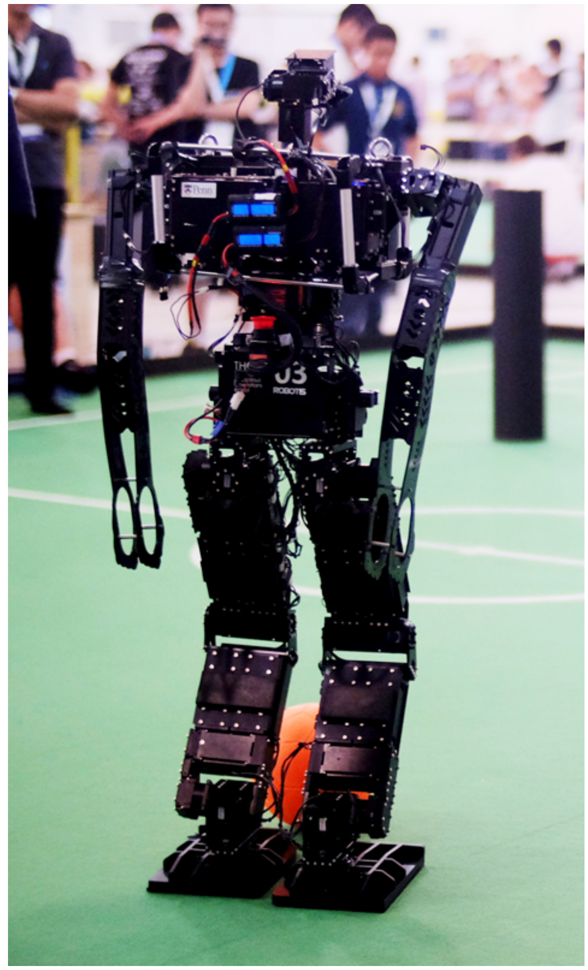

Fig. 1. The modified THOR-OP robot playing soccer at RoboCup 2014.

achieving the footholds. This method has been implemented on various humanoid robot platforms and has been used successfully for various tasks such as stepping over obstacles [1] and climbing stairs[2]. However, the main drawback of this method is that, by requiring a future ZMP trajectory, it does not allow for reactive movements needed for push recovery or responses in dynamic environments. Additionally, this method relies on an optimization over the future time steps, which generally requires more computational power than simple methods. On the other hand, there are a number of simple, reactive bipedal walk controllers based on a number of simplifying assumptions. One variant of these approaches is the central pattern generator (CPG), which uses a number of simple basis functions to generate the COM trajectory without explicitly considering the ZMP criterion. Due to its

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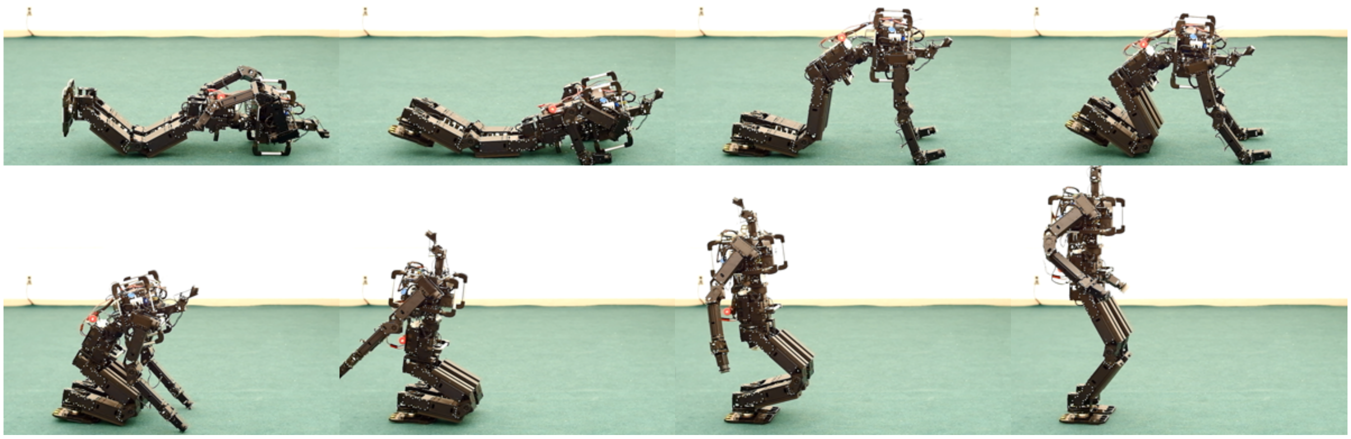


Fig. 2. THOR-OP robot performing getup motion from the prone posture

simplicity, this approach has been widely used for small, resource constrained humanoid robots [3], [4], and on the the HUBO full sized humanoid robot with help of feedback stabilization [5]. Approaches that use the analytical solution of the ZMP equation generate a COM trajectory for each step, assuming a ZMP trajectory represented by limited order polynomials [6], [7], [8], [9]. Both approaches have little control latency and are computationally efficient, but they can be less stable than ZMP preview methods since changes in walk velocity can result in ZMP fluctuations.

To have the best of both methods, we have presented a hybrid walk controller implemented for a small humanoid robot [10]. This controller switches between a reactive walk controller that changes the walk velocity instantaneously and a preview walk controller that can handle complex stepping requirements without inducing jerkiness in trajectories. The nature of robot soccer requires dynamic maneuvers to deal with obstacles, a moving ball and opponents, while avoiding ZMP fluctuations that cause deleterious instabilities on large platform. In this work, we describe how we utilize the hybrid walk controller for the locomotion and kick generation of a full sized general purpose robot. We validate our approach experimentally on the THOR-OP full sized humanoid robot and in competition at RoboCup 2014.

The remainder of the paper proceeds as follows. Section II describes the THOR-OP general purpose humanoid robot platform. Section III describes how we utilize the hybrid walk controller to generate walk and kick motions that are needed for the robot soccer game. Sections IV show results from a physics-based simulation and experiments using the THOR-OP humanoid robot. We conclude with a discussion of potential future directions arising from this work.

II. THOR-OP Humanoid Robot Platform

The THOR-OP humanoid robot is developed by Robotis, Co. Ltd[1] as a general purpose disaster response robot to compete in the DARPA Robotics Challenge (DRC) [11]. The DRC requires a complete system with the mobility, dexterity, strength and endurance for a practical disaster response situation. In order to score in the various DRC tasks, the robot should be able to operate in unstructured environments that include rough terrain, ladders, doorways, piles of debris, and industrial valves. It is also crucial that the robot be capable of maneuvering unmodified power tools and vehicles designed for use by human beings. THOR-OP performed well during the DRC Trials and is among the finalists for the DRC Final in 2015, showing to be an advanced and comprehensive humanoid platform.

TABLE I

Specs of adult-size humanoid robots in RoboCup 2012-2014

Team	**Robot**	**Height** (cm)	**Weight** (kg)
EDROM	MABI	134	7
Team Sweaty	Sweaty	140	11.5
Team Charli	CHARLI-2	140	12.1
HuroEvolution AD	HuroEvolution	149	15
Tsinghua Hephaestus	THU_Strider	132	18.1
TU Eindhoven	TUlip	125	23
JoiTech	Tichno-RN	150	25
KW-1	KW-1	152	26
Robo-Erectus	Sr-2001	150	44
THORwIn	THOR-OP	147	43.6 / 51.6

As shown in Table I, most of the adult-size humanoid soccer robots are designed solely for soccer playing and extremely light-weight. They are relatively simple in terms of kinematics, lacking high DOF upper bodies necessary for manipulation tasks. In comparison to these single-purpose robots, THOR-OP has more DOF (waist pitch and yaw and 7DOF in arms) and a stronger mechanical structure for manipulating heavy tools and performing whole body movements such as get-up motion necessary on soccer fields and other challenging terrains (shown in Figure 2). During the DRC Trials, THOR-OP robot successfully accomplished demanding tasks such as manipulating a drill, dragging the

[1]http://www.robotis-shop-en.com/

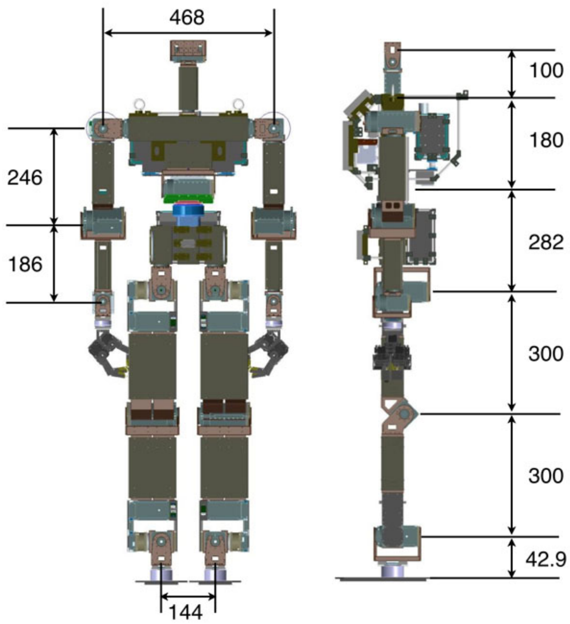


Fig. 3. Front and side views of the THOR-OP robot with dimensions. (unit: *mm*)

fire hose and turning tight valves.

A. Actuators and Structural Components

The off-the-shelf Pro series of Dynamixel actuators developed by Robotis, Co. Ltd power most high-load joints. THOR-OP utilizes three different types of Dynamixel Pro actuator, rated at 20W, 100W and 200W, which are fitted with different reduction gear boxes. In addition to the actuators, the robot is mainly built with standardized structural components that are simply extruded aluminum tubings and brackets with regularly spaced bolt holes, and one can easily assemble them with hex bolts. Figure 4 shows the structural components required for a single THOR-OP robot; twenty four total man-hours is estimated to complete assembly from parts.

B. Modification for Robot Soccer

THOR-OP originally had 7DOF arms and two grippers with underactuated fingers providing a large workspace and high dexterity for manipulation tasks. However the arms were too long to conform with the RoboCup rules and high DOF arms are not necessary for the soccer games. A shorter and simpler arm design was therefore introduced which used acrylic rather than metal, sparing 4kg in weight from each arm. Since the new arms were slimmer and stayed closer to the torso while the robot is walking, resulting in a narrower stance, the robot had better chance of successfully avoiding obstacles. Moreover, the modified arm consisted of only 2 DOF (shoulder pitch and roll) and used less powerful Dynamixal servos, and THOR-OP still had enough range of motion and strength for picking up and holding a ball, which are needed for manipulation in a soccer game.

We also modified the feet of THOR-OP. The original feet were designed to be small to traverse uneven terrain better,

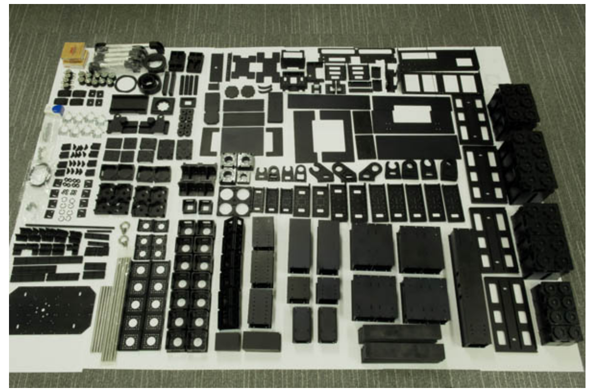


Fig. 4. The structural components for a single THOR-OP robot use standardized dimensions.

yet not ideal for the robot soccer where robot is supposed to walk over relatively flat surface. We have made slightly bigger feet with a short wall, a 'kicker', at the toe section of each foot. Through testing and competition, we found that the increased dimensions of the feet proved to provide better support and to increase the walking speed of the robot, and the 'kicker' helped the robot kick straight even with a slight misalignment.

III. Hybrid Walk Controller

In a previous work [10], we have suggested a hybrid walk controller that dynamically switches between the analytic ZMP based reactive controller and ZMP preview controller, and tested this controller using a small DARwIn-OP humanoid robot. The robot mainly used the reactive controller for locomotion; the ZMP preview controller was used only to perform more complex footstep motions such as dynamic kicking.

On the larger and heavier THOR-OP robot, when using the reactive controller, the sudden transition between double and single support can induce harmful jerks due to greater inertia and different dynamic properties of the robot. We therefore use the hybrid walk controller to handle explicitly the transitions between the double support phase and single support phase.

A. Support Change Motion Generation

We use the ZMP preview controller to generate the initial and final steps where the transitions between single and double support take place. To simplify designing the ZMP trajectory for the ZMP preview controller, we have used the same trapezoidal ZMP trajectory as the one for our reactive controller. Each preview step can be defined in the following way:

$$PS_i = \{SF,\ t_1,\ t_2,\ t_{STEP},\ FOOT_{MOD},\ ZMP_{MOD},\ FT\} \quad (1)$$

where SF is the support foot, t_1 the duration of the first ZMP slope, t_2 the duration of the second ZMP slope, t_{STEP} the whole duration of the step, $FOOT_{MOD}$ the target displacement of the swing foot for the step in (x, y, ϕ), ZMP_{MOD} the relative ZMP position from the support foot center, and FT the foot trajectory type. We add the initial and final preview

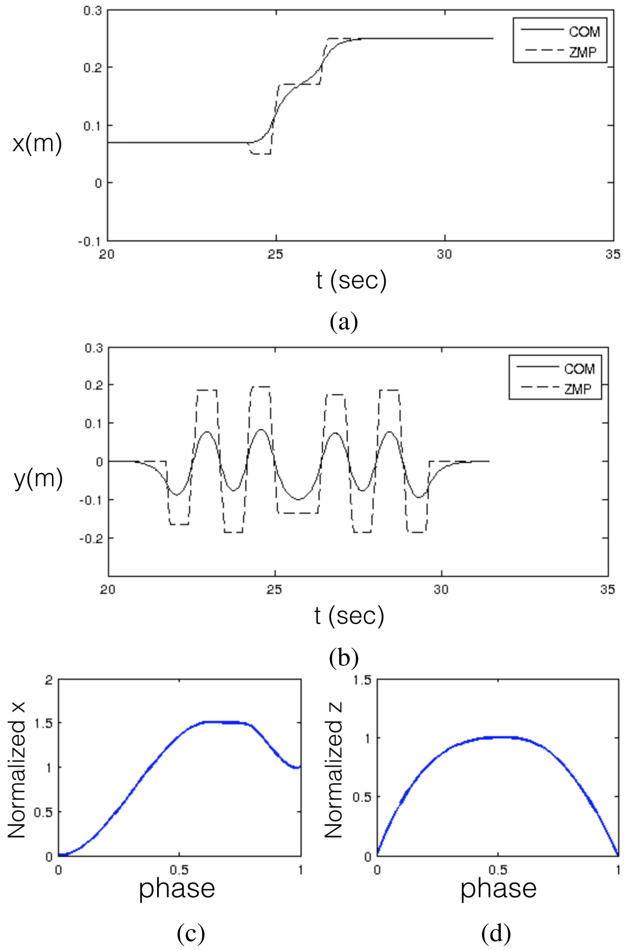


Fig. 5. COM, ZMP and foot trajectories during fast kick motion. (a) X axis COM and ZMP trajectories (b) Y axis COM and ZMP trajectories (c) X axis foot trajectory during kick step (d) Z axis foot trajectory during kick step

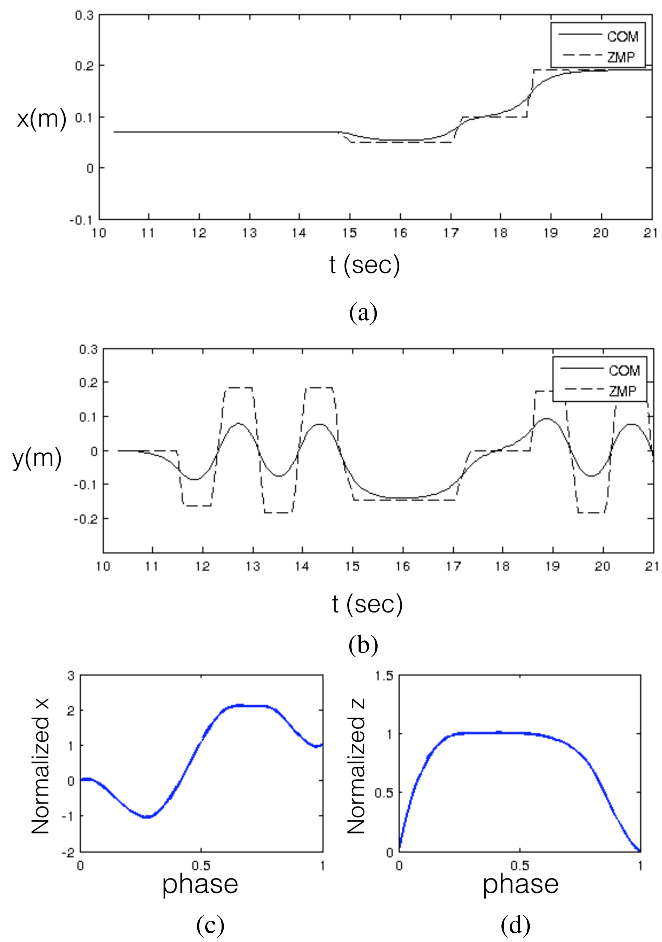


Fig. 6. COM, ZMP and foot trajectories during strong kick motion. (a) X axis COM and ZMP trajectories (b) Y axis COM and ZMP trajectories (c) X axis foot trajectory during kick step (d) Z axis foot trajectory during kick step

step entries into the step queue to initiate the initial and final steps. The initial step has zero foot displacement while the final step is set to make both feet parallel.

B. Kick Motion Generation

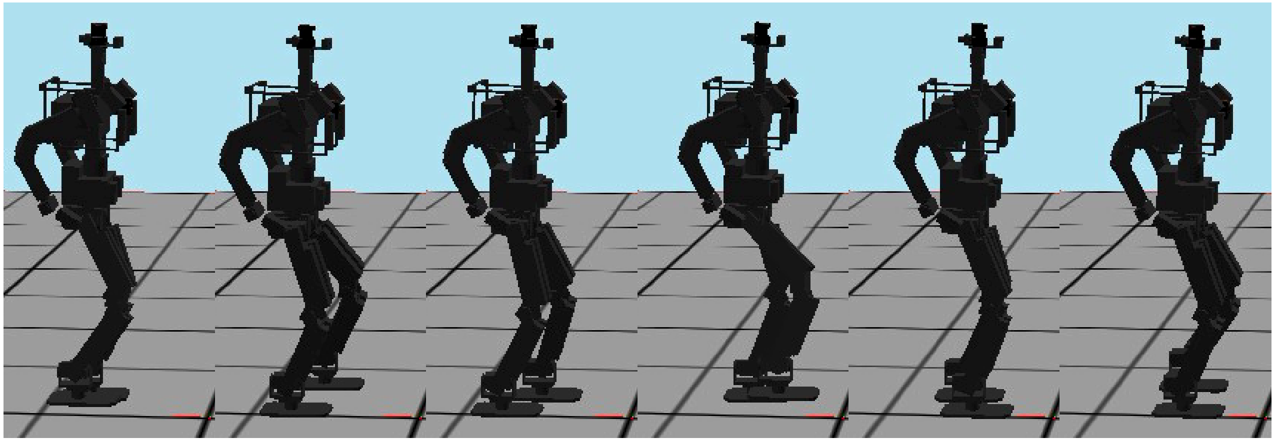
We also use the hybrid walk controller formulation to generate the dynamic kick motion for the robot. A number of different dynamic kick motions are needed for the competition, because the attacker loses its penalty kick attempt if any of the following situations happens: direct scoring from the defensive half of the field, robot touching any of obstacles, and the kicked ball stopping inside the penalty box. Under those rules, the best strategy is to move the ball to cross the centerline first and do a strong kick to score.

We designed three different kick motions. A fast kick with three to four meters of kicking range moves the ball to the opposite field. A weak kick with a one meter kicking range moves the ball close to the middle of the field. Last but not least, a slow and strong kick can direct score. To define the kick motion, we use a number of the preview step structures for each step of the kick. Thanks to our hybrid walk controller formulation, we can use a single kick motion to initiate the kick in any phase of the walking. Figure 5 and 6 shows the COM, ZMP and foot trajectories of two different kicks we have used for the competition.

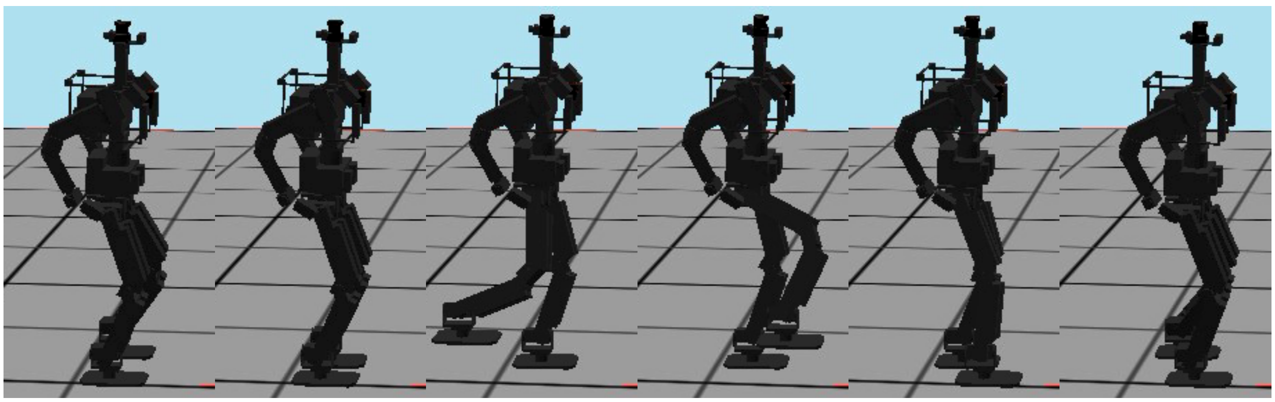
IV. Simulation and Experimental Results

We first used the Webots simulator to replicate the competition environment and check the time limits. From a number of simulator runs, where the initial positions of the ball and obstacles varied a lot, we found that the stride length of 30cm is enough to make the attacker robot score a goal within the time limit of 90 seconds for all tested scenarios. Figure 7 shows the sequence of the THOR-OP robot performing two motions in simulated environment.

The hybrid walk controller has been used successfully on the actual robot during the RoboCup competition, with very little parameter tuning required. We did not experience stability issues during the competition. As in simulation, the robot could kick the ball to the goal within the time limit almost every time. In the artificial grass challenge, the robot stably achieved a stride length of 40cm per step over cushy artificial grass terrain.



(a) Fast kick



(b) Strong kick

Fig. 7. Simulated THOR-OP robot performing a dynamic kick in middle of reactive walking

Figure 8 shows two kick sequences that our robot utilized during the RoboCup competition. Although our hybrid walk controller allows initiation of any dynamic kick motion during locomotion, we limited the strong kick to always start from double support since initiating a big kick while walking led to inconsistent kick distances. With this limitation, the kick distances from each kick are predictable and consistent. The fast kick achieves a range between 3.8m and 4.2m, while the strong kick always has more than a 10 meter range.

Although we have been developing and testing our kick motion generation model using the modified version of THOR-OP with bigger feet for the RoboCup competition, we found that our hybrid controller can perform well without much tuning or modifications in the DRC version of THOR-OP with regular sized feet, making it walk and kick stably, shown in Figure 9.

V. Conclusions

In this work, we described how we utilize a hybrid walk controller to generate the walk and kick motions for a heavy, general purpose, full sized humanoid robot. The hybrid walk controller helps the robot to initiate and end locomotion smoothly. Additionally, it allows the robot to perform various dynamic kicks without stopping. This ability has helped greatly in the RoboCup 2014 competition and our team won the first place in the Humanoid AdultSize League.

Acknowledgments

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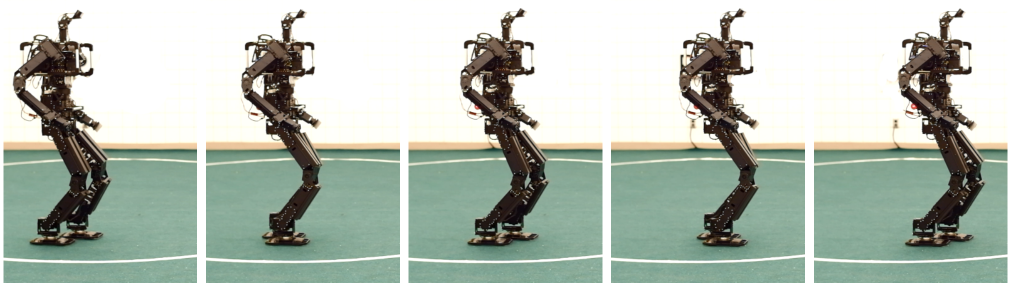
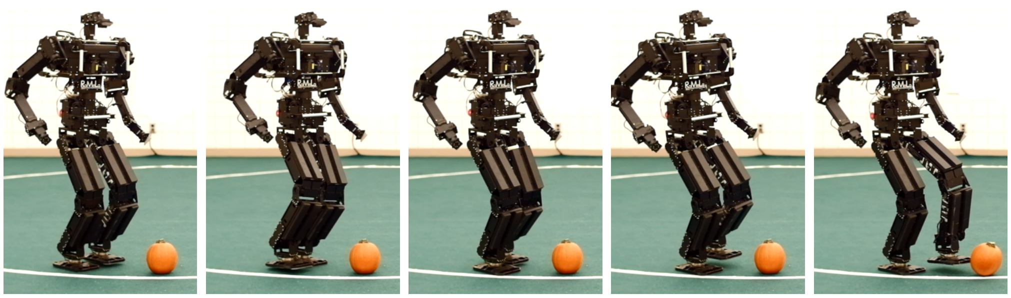
(a) Fast kick

(b) Strong kick

Fig. 8. THOR-OP performing a dynamic kick in the middle of reactive walking.



(a)



(b)

Fig. 9. THOR-OP robot performing (a) dynamic walking with reactive controller (b) dynamic kicking during locomotion

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