Proceedings of the ASME 2011 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC/CIE 2011
August 28-31, 2011, Washington, DC, USA

DETC2011-48412

DEVELOPMENT OF A FULL-SIZED BIPEDAL HUMANOID ROBOT UTILIZING SPRING ASSISTED PARALLEL FOUR-BAR LINKAGES WITH SYNCHRONIZED ACTUATION

Jeakweon Han
Robotics and Mechanisms Laboratory
Department of Mechanical Engineering
Virginia Tech.
Blacksburg, Virginia 24061, USA
jk4robot@vt.edu

Dennis Hong, Ph.D.
Robotics and Mechanisms Laboratory
Department of Mechanical Engineering
Virginia Tech.
Blacksburg, Virginia 24061, USA
dhong@vt.edu

ABSTRACT

Besides the difficulties in control and gait generation, designing a full-sized (taller than 1.3m) bipedal humanoid robot that can walk with two legs is a very challenging task, mainly due to the large torque requirements at the joints combined with the need for the actuators' size and weight to be small. Most of the handful of successful humanoid robots in this size class that exist today utilize harmonic drives for gear reduction to gain high torque in a compact package. However, this makes the cost of such a robot too high and thus puts it out of reach of most of those who want to use it for general research, education and outreach activities. Besides the cost, the heavy weight of the robot also causes difficulties in handling and raises concerns for safety.

In this paper we present the design of a new class of full-sized bipedal humanoid robots that is lightweight and low cost. This is achieved by utilizing spring assisted parallel four-bar linkages with synchronized actuation in the lower body to reduce the torque requirements of the individual actuators which also enables the use of off the shelf components to further reduce the cost significantly. The resulting savings in weight not only makes the operation of the robot safer, but also allows it to forgo the expensive force/torque sensors at the ankles and achieve stable bipedal walking only using the feedback from the IMU(Inertial Measurement Unit.) CHARLI-L (Cognitive Humanoid Autonomous Robot with Learning Intelligence - Lightweight) is developed using this approach and successfully demonstrated untethered bipedal locomotion using ZMP (Zero Moment Point) based control, stable omni-directional gaits, and carrying out tasks autonomously using vision based localization.

INTRODUCTION

Since the debut of Honda's P2 humanoid robot in 1996 [1], efforts in developing full-sized humanoid robots around the world resulted in a number of successful designs. WABIAN of Waseda University [2], HRP series of JAIST [3], HUBO of KAIST [4] and JOHNNIE of Technical University of Munich [5] are some good examples. One of the biggest challenges in the development of such robots is to design the joints for the lower body that can produce enough torque to handle the static and dynamic loads while being compact enough to be packaged in the constrained space within the robot. To achieve this, most of these robots use DC servomotors with harmonic drives for actuation and gear reduction, but this approach makes them heavy and expensive.

In this paper, we present a design of a new class of full-sized bipedal humanoid robots that is lightweight and low cost. This is achieved by utilizing spring assisted parallel four-bar linkages with synchronized actuation in the lower body to reduce the torque requirements of the individual actuators which also enables the use of off the shelf components to further reduce the cost significantly. The approach of using of a four-bar linkage as a mechanism for bipedal robots has been suggested before. Arnaud Hamon et. al. [6] presented a cross four-bar linkage design for the knee joint to take advantage of the spring force. The results from the simulation have shown that the spring could be used for making the system more energy efficient. J. McKendry et. al. [7] developed a new kinematic mechanism for a bipedal robot which consists of several four-bar linkages with a single actuator. However, it used three legs to stabilize the body. Hyeung-Sik Choi, et. al.[8]

Figure 1. Humanoid robot CHARLI-L

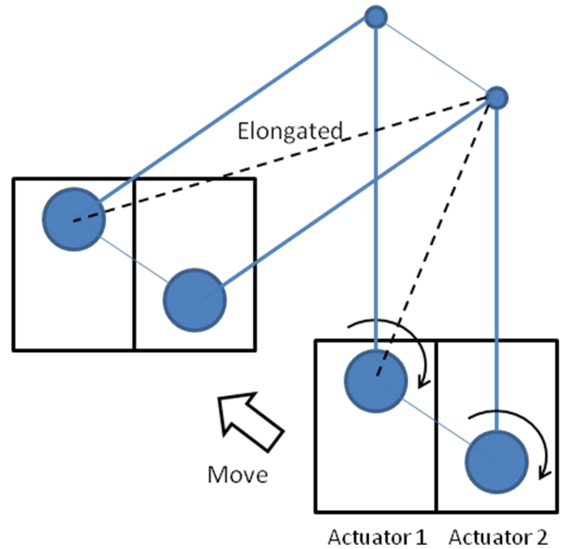


Figure 2. Spring Assisted Parallel Four-bar Linkage with Synchronized Actuation

and Thomas Buschmann et. al. [9] used four-bar linkages to translate linear actuation to rotational motion for a joint in a bipedal robot.

In this paper we present the design of a new class of full-sized bipedal humanoid robots that is lightweight and low cost. This is achieved by utilizing spring assisted parallel four-bar linkages with synchronized actuation in the lower body to reduce the torque requirements of the individual actuators which also enables the use of off the shelf components to further reduce the cost significantly. The resulting savings in weight not only makes the operation of the robot safer, but also allows it to forgo the expensive force/torque sensors at the ankles and achieve stable bipedal walking only using the feedback from the IMU(Inertial Measurement Unit.) CHARLI-L (Cognitive Humanoid Autonomous Robot with Learning Intelligence - Lightweight) is developed using this approach and successfully demonstrated untethered bipedal locomotion using ZMP (Zero Moment Point) based control, stable omnidirectional gaits, and carrying out tasks autonomously using vision based localization.

THE CONCEPT OF THE MECHANICAL DESIGN

The novel concepts of the proposed mechanical design of CHARLI-L's leg design can be summarized into three main parts; a parallel four-bar linkage, a synchronized actuator, and a tensional spring. Among the three, the parallel four-bar linkage is the key element that holds all three elements together.

Unlike conventional full size humanoid robot designs, CHARLI-L does not use gear reduction mechanisms such as harmonic drives. Instead, to reduce the weight, multiple, distributed small actuators are used. Synchronizing the actuators allows the smaller and lower torque actuators and off-the-shelf components to be utilized. While dual inline actuators could accomplish the same goal, the parallel four-bar linkage proves a compact solution. Figure 2 shows the parallel four-bar linkage with the orientation of the two actuators. Assuming the two actuators simultaneously move with identical torque, the torques of the actuators will combine and the overall torque can be double, theoretically.

Besides this, there are two more advantages of the parallel four-bar linkage. First, the degree of freedom (DOF) of the leg can be reduced, so that the number of actuator reduced saving weight. 6 is known as the minimum number of DOF to generate general motion, so most bipedal robots use a serial chain configuration of 6 DOF for their leg designs. However, by assuming the robot is only walking on flat horizontal ground, the foot can be constrained to be always parallel to the flat ground, allowing to generate a walking pattern with only 5 DOF. Using one set of the parallel four-bar linkage for the thigh and one for the shin, the hip joint will be constrained parallel to the ankle joint. Thus, using two sets of parallel four-bar linkages, only 5 actuator sets (5DOF) can be used to generate a walking pattern.

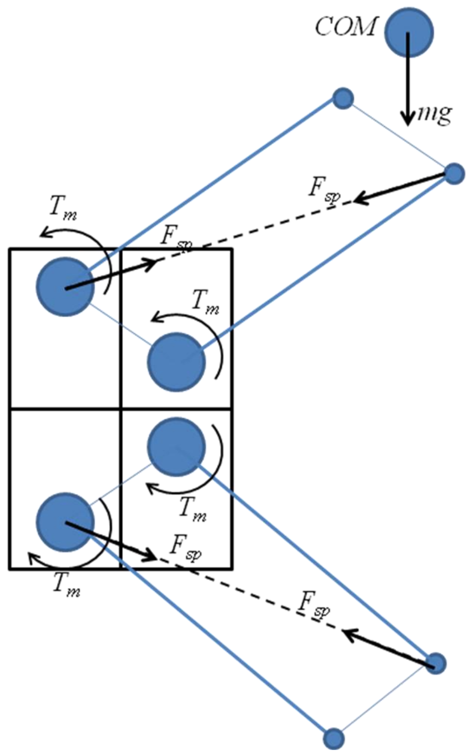


Figure 3. Diagram of CHARLI-L's Leg

Second advantage of the parallel four-bar linkage approach is that additional torque can be provided from a tensional spring. Figure 2 shows the length of one diagonal line of the parallelogram elongates, when the four-bar linkage moves (the direction of the arrow.) If the tensional spring is installed on this diagonal line, this spring stretches out and creates a tensile force, as the linkage moves. This tensile force contributes to moving the link to the initial position. When CHARLI-L walks and the leg pushes up the upper body, the torques of the actuators and the forces of the springs work together shown in figure 3 reducing the required torque of the actuators.

SIMULATION FOR THE DESIGN

Due to the parallel four-bar linkage mechanism, CHARLI-L does not need a hip actuator or an ankle actuator for pitch motion control. This allows forward and backward walking with only two sets of knee actuators. Thus, these knee actuators are the key element to make CHARLI-L walk. Figure 4 shows the torque requirements of the knee joint, when it pushes up the upper body for standing up. As the robot sits down,, the knee joint needs more torque to resist the upper body due to the longer moment arm.

CHARLI-L uses the Dynamixel EX-106+ motor as the knee actuator due to its effective power to weight ratio and affordable price. In addition, the built-in synchronizing function

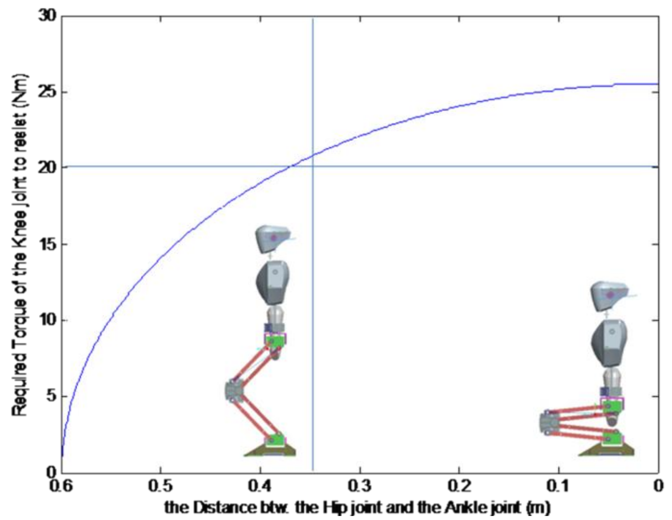


Figure 4. Required Torque of the Knee Joint

provides an easy and reliable method to actuate two motors in tandem. The maximum holding torque of one actuator is only 10Nm. Thus the maximum holding torque with the synchronizing function, theoretically, is only 20Nm. The simulation results in figure 4 show the knee joint needs more than 25Nm to stand up. While walking, the moment arm changes in a range from 0. 35m to 0.6m requiring at least 21Nm torque. This shows that CHARLI-L cannot walk with synchronized EX-106+ actuators alone.

To remedy this problem without resorting to higher power actuators, which will increase the weight and cost of the robot, a tension spring with a cleaver configuration is used to reduce the torque requirements of the actuators. Figure 5 shows the design of the parallel four-bar linkage with a tensional spring between the two facing joints. Equation 1 calculates the torque resulting from the spring. According to this, as the angle between link 1 and link 2 increases, the spring torque increases until it reaches 148 degree. The spring torque assists the actuators to support

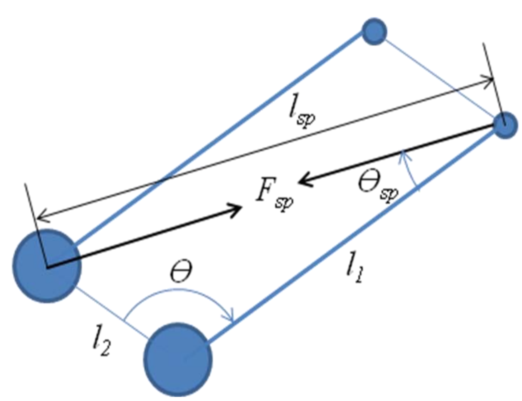


Figure 5. Diagram of Four-bar Linkage with Spring Force

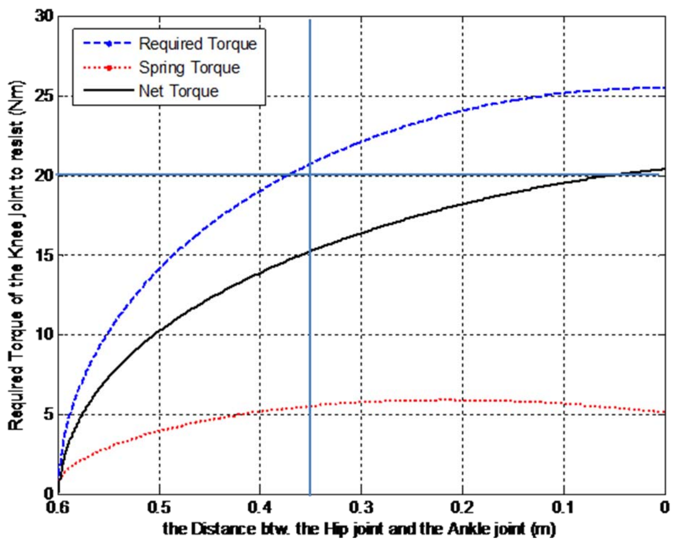


Figure 6. Torque requirements of the Knee Joint with Tensional Springs

$$T_{\mathrm{spring}} = k\,\frac{l_1 l_2 \left(l_{\mathrm{sp}} - l_0\right)}{l_{\mathrm{sp}}}\sin\theta \qquad \text{(Eq.1)}$$

Here, $l_{\mathrm{sp}} = \sqrt{{l_1}^2 + {l_2}^2 - 2 l_1 l_2 \cos\theta}$

the weight of the upper body so the required actuator torque is reduced.

Figure 6 shows the torque requirements at the knee joint with the addition of a tensional spring. A spring constant of 980N/m was selected and doubled, because one parallel four-bar linkage has two springs installed for symmetry. The dashed blue line is the required torque of the knee joint, the same as in figure 4, and the dotted red line is the torque generated by the spring. The black line shows the reduced required net torque due to the spring.

During walking (0.35m~0.6m), the maximum required torque of actuator is 15Nm with the spring which is smaller than maximum torque of synchronized actuators, 20Nm. A bigger spring constant could be selected to further reduce the actuator's toque requirement but can cause additional torque requirements when CHRALI-L lifts up a leg. This is also related to the actuator's velocity and a damping effects, so 25% reduction in torque was chosen as a design margin and a spring constant of 980N/m was chosen based on this calculation.

Figure 7 shows the CAD model of CHARLI-L's leg configuration. The actuators for the pitch direction are located in the knee area, while hip and ankle actuators are used for the roll direction only. The total weight of the lower body is 6.3kg

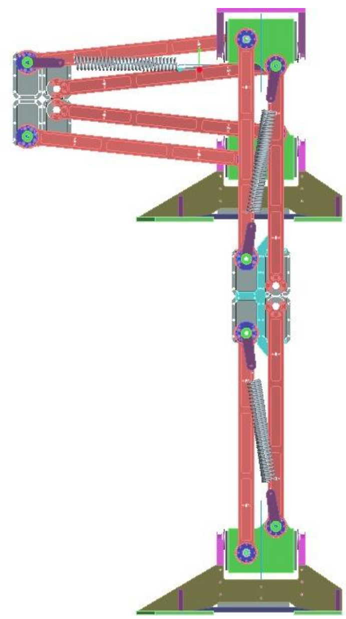


Figure 7. Leg Design of CHARLI-L

with the actuators weighting a total of 2.7kg, 43% of the total weight. This proposed mechanism significantly reduced the weight of the robot compared to other humanoid robots in the same class. For example, the weight of one servo actuator module producing 80Nm maximum torque including harmonic drive is about 2kg. If a robot uses 12 actuator for a lower body,

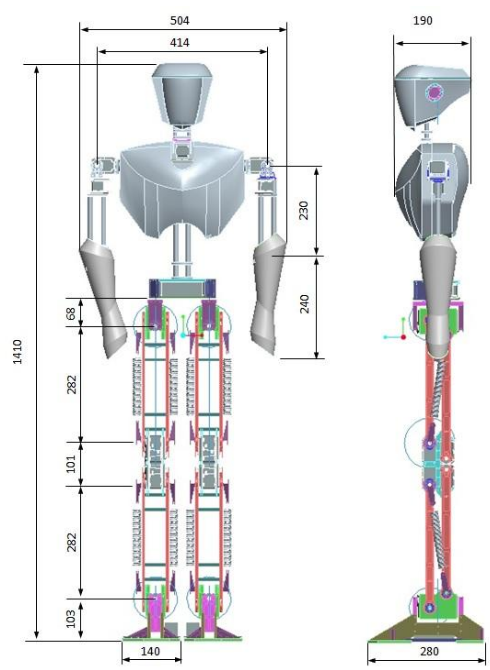


Figure 8. Dimensions of CHARLI-L

Table 1. The Specifications of CHARLI-L

Height (mm)		1410
Weight (kg)		12.7
DOF	Leg	5 x 2
	Arm	4 x 2
	Head	3
	Total	21
Actuator (Dynamixel)	Leg	EX-106+ x 18
	Arm	RX-64 x 4, RX-28 x 4
	Head	RX -28 x 3
Sensor	IMU	3DM-GX3-25
Control System	HW	FitPC2
	SW	Ubuntu 10.04, C++
Power	Actuator	LiPo 2200mAh 18.5V x3
	Computing	LiPo 1100mAh 11.1V

the total weight of the actuators would be around 20kg. That is the main reason why full size humanoid robots are so heavy. The weight of a lower body is normally known as around 30kg. CHARLI-L's lower body is only one fifth of the weight of robots in the same class.

SPECIFICATIONS OF CHARLI-L

Figure 8. shows the overall dimensions of CHARLI-L. The detailed specifications are shown in table 1.

KINEMATICS

Closed form solutions of the forward and inverse kinematics for the lower body are important for generating the patterns for walking. Otherwise, the computer has to use numerical analysis methods to calculate the appropriate position and angle of the foot which normally takes too much time to be implemented for real-time walking gaits.

Figure 9. shows the kinematic configuration of the left leg. Equations 2 and 3 are the solutions of the forward and the inverse kinematics for this leg respectively.

In equation 2., x, y and z are the foot position coordinates with respect to the origin located in the hip. The foot position is calculated from the joint angles.

In equation 3., Θ_1 to Θ_5 are the angle of the joints and Θ_F is the angle of the foot in z direction. The x and y direction angles are not necessary to express foot's position, because the foot is always parallel to the ground. The joint angles are calculated from the foot's position and the angle in z direction.

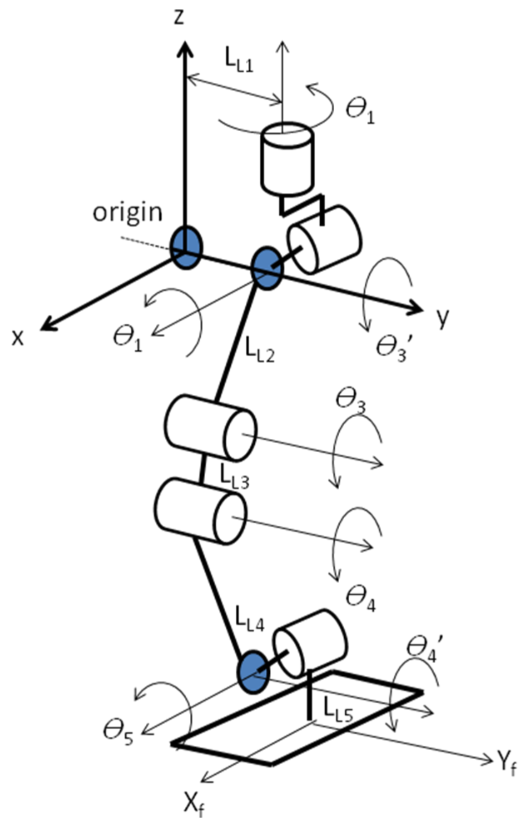


Figure 9. Configuration of the Left Leg

$$\theta_F = \theta_1$$

$$\begin{aligned} x = & -L_{L2}\sin\theta_1\sin\theta_2(\cos\theta_3+\cos\theta_4) \\ & + L_{L2}\cos\theta_1(\sin\theta_3-\sin\theta_4) \\ & + L_{L3}\sin\theta_1\sin\theta_2 + L_{L5}(-\sin\theta_1\sin\theta_2\cos\theta_5 \\ & + \sin\theta_1\cos\theta_2\sin\theta_5) \end{aligned}$$

(Eq.2)

$$\begin{aligned} y = & L_{L2}\cos\theta_1\sin\theta_2(\cos\theta_3+\cos\theta_4) \\ & + L_{L2}\sin\theta_1(\sin\theta_3-\sin\theta_4) \\ & + L_{L3}\cos\theta_1\sin\theta_2 + L_{L5}(\cos\theta_1\sin\theta_2\cos\theta_5 \\ & + \cos\theta_1\cos\theta_2\sin\theta_5) \end{aligned}$$

$$\begin{aligned} z = & -\cos\theta_2(L_{L3}+L_{L2}(\cos\theta_3+\cos\theta_4)) \\ & + L_{L5}(-\cos\theta_2\cos\theta_5+\sin\theta_2\sin\theta_5) \end{aligned}$$

$$
\begin{aligned}
\theta_1 &= \theta_F \\
\theta_2 &= \tan^{-1}\left(\frac{x - y - (x\cos\theta_1 + y\sin\theta_1)\,(\cos\theta_1 - \sin\theta_1)}{z(\cos\theta_1 + \sin\theta_1)}\right) \\
\theta_5 &= -\theta_2 \\
\theta_3 &= \tan^{-1}\left(\frac{(1+\cos\gamma)\alpha + \sin\gamma\cdot\beta}{-\sin\gamma\alpha + (1+\cos\gamma)\beta}\right) \\
\theta_4 &= \gamma - \theta_3
\end{aligned}
\qquad \text{(Eq.3)}
$$

here, $\alpha = \dfrac{x\cos\theta_1 + y\sin\theta_1}{L_{L2}}$

$$\beta = -\frac{1}{L_{L2}}\left(\frac{z}{\cos\theta_2} + L_{L3}\right)$$

$$\gamma = \cos^{-1}\left(\frac{\alpha^2 + \beta^2 - 2}{2}\right)$$

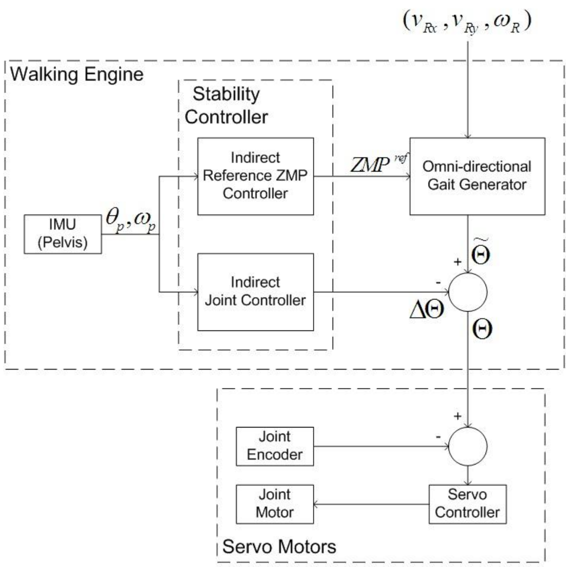
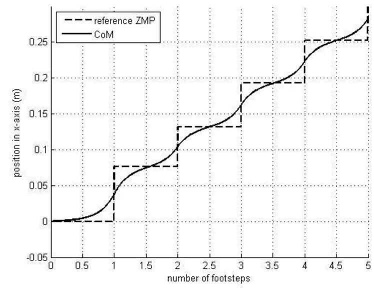


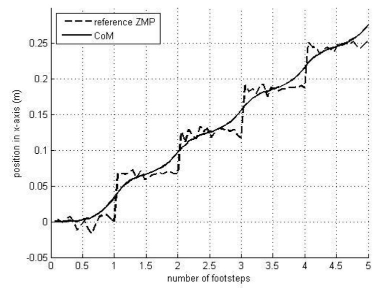
Figure 10. Block Diagram of Walking Engine

WALKING ENGINE

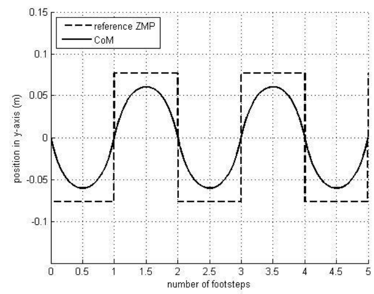
Figure 10 shows the block diagram of CHRALI-L's omni-directional walking engine. Given the direction and walking speed along with the step size, the gait generator in the walking engine calculates the appropriate foot position and actuator angles using inverse kinematics. Then, the walking engine sends these angles to the joint actuator controllers. This allows real time and omni-directional walking. However, unlike miniature bipedal robots which can achieve stable walking with only using inverse kinematics and without any stabilization feedback, full-sized bipedal robots such as CHARLI-L require active stabilization methods due to the large inertia forces. CHARLI-L's walking algorithm relies on ZMP (Zero Moment Point) control and utilizes the feedback from the IMU to stabilize the gait. Details of CHARLI-L's walking engine is presented in. [10]



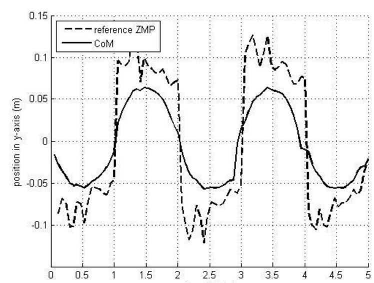
(a)



(b)



(c)



(d)

Figure 11. ZMP and CoM graphs from walking test
(a) x directional reference curve
(b) x directional feedback curve
(c) y directional reference curve
(d) y directional feedback curve

TEST RESULTS

Figure 11 shows the plots of the reference and feedback ZMP and CoM trajectories with respect to x and y directions from a walking test. Feedback data are obtained from the IMU. These results show that CHARLI-L follows the planed trajectory well, although wobbles can be observed. Figure 12 is a sequence of images of CHARLI-L walking captured from the video of the waking test. It shows CHARLI-L's ability to walk in an omni-directional manner stably. [10].

DISCUSSION

This paper presents a new approach in mechanical design for a full-sized humanoid robot. Instead of the typical serial chain configuration, a double parallel four-bar linkage mechanism was chosen for the leg configuration to reduce the cost and weight. Two sets of parallel four-bar linkages allowed CHARLI-L's leg to have a 5 DOF configuration compared to the typical 6 DOF of other robots while allowing the full motion needed for omni-directional walking by constraining the orientation of the foot parallel to the ground. This configuration also allows the use of a set of tensional springs to reduce the torque requirements at the individual actuators. Synchronizing the actuators to work in tandem allowed the design to use smaller and lower torque actuators and off-the-shelf components to further reduce the cost and weight of the robot.

The resulting 141 cm tall autonomous robot is able to walk omni-directional and in a stable manner while being one-fifth lighter than other humanoid robots in the same class and also at a fraction of the cost.

ACKNOWLEDGMENTS

The authors would like to recognized the National Science Foundation and the Office of Naval Research for partially supporting this work through grants OISE 0730206, CNS 0960061, CNS 0958406, and ONR 450066

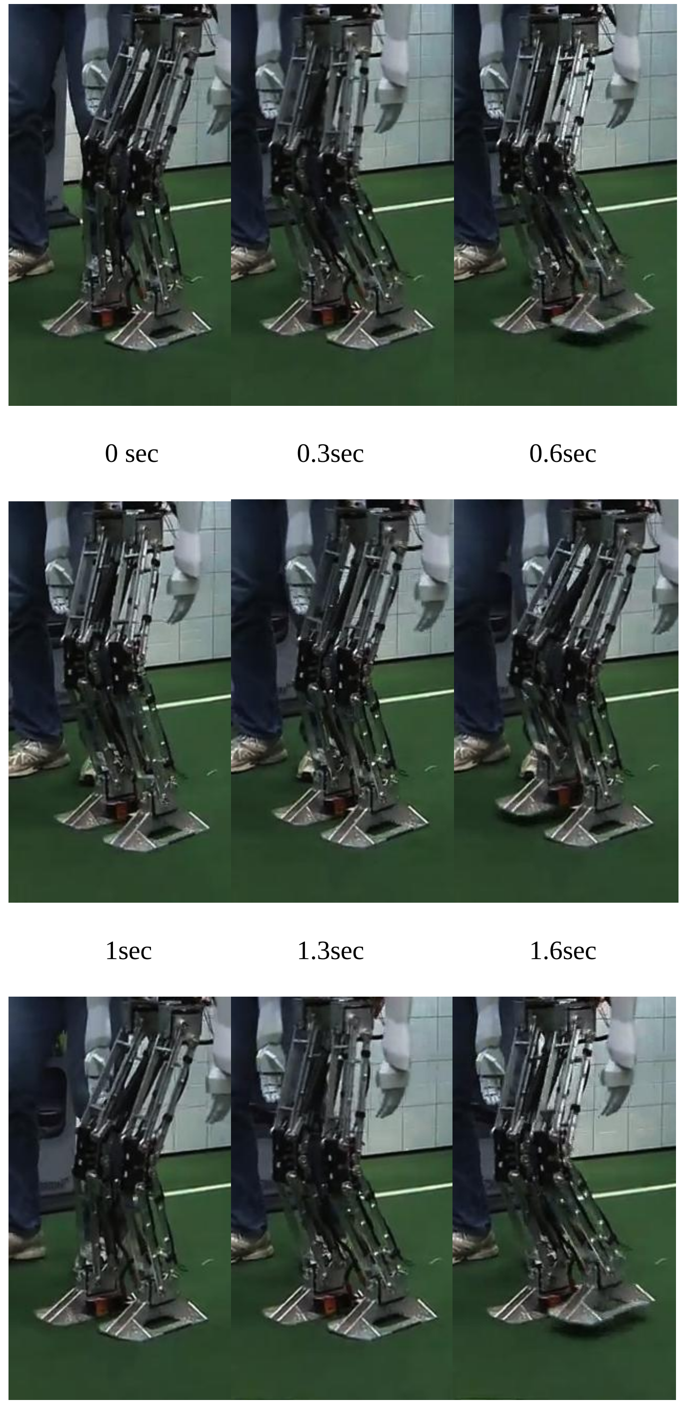
REFERENCES

[1] Hirose, M., et. al., "Humanoid Robot", In Journal of the Robotics Society of Japan, Vol. 15, No.7. pp983-985, 1997

[2] S. Hashimoto, et. al., "Humanoid Robots in Waseda University - Hadaly-2 and WABIAN", In Journal of Autonomous Robots, Vol. 12, No 1., pp25-38, 2002

[3] Yokoi Kazuhito, et. al., " Humanoid Robot HRP-2 ", Journal of the Japan Society of Mechanical Engineers, VOL.109, NO.1051, pp.438-439, 2006

[4] Ill-Woo Park, Jun-Ho Oh, et. al., "Mechanical design of Humanoid Robot Platform KHR-3 (KAIST Humanoid Robot 3: HUBO)",Humanoid Robots, 5th IEEE-RAS International Conference., pp.321-326, 2005



0 sec 0.3sec 0.6sec

1sec 1.3sec 1.6sec

2sec 2.3sec 2.6sec

Figure 12. Sequence of images from the video of the walking

[5] M. Gienger, K. Löffler, and F. Pfeiffer, "Towards the Design of Biped Jogging Robot", Proc. IEEE Int. Conference on Robotics and Automation, pp. 4140-4145, 2001.
[6] Arnaud Hamon, Yannick Aoustin, "Cross Four-Bar Linkage for the Knees of a Planar Bipedal Robot", Humanoids2010 Conference, 2-24.
[7] J. McKendry, B. Brown, E.R. Westervelt, and J.P. Schmiedeler, "Kinematic Design and Dynamic Analysis of a Planar Biped Robot Mechanically Coordinated by a Single Degree of Freedom" , 2007 IEEE International Conference on Robotics and Automation
[8] Hyeung-Sik Choi, Yong-Heon Park,"Development of a biped walking robot actuated by a closed-chain mechanism", Robotica(2006), Vol.24: Issue 1, p.31-37
[9] Thomas Buschmann, Sebastian Lohmeier, Heinz Ulbrich, "Humanoid robot Lola: Design and walking control", Journal of Physiology - Paris 103 (2009) 141–148
[10] Seungmoon Song, Young-Jae Ryoo, Dennis W. Hong, "Development of an Omni-directional Walking engine for full-sized lightweight humanoid robots", IDETC/CIE 2011 Conference, DETC2011-48786