Development of a Biped Walking Robot with Antagonistic Actuation

Takashige Yano, Jae Hoon Lee, and Shingo Okamoto
Graduate School of Science and Engineering, Ehime University, Matsuyama, Japan
Email: lee.jaehoon.mc@ehime-u.ac.jp

***Abstract*— This research was intended at developing a biped walking robot with antagonistic actuation for realizing stable walking motion. A three-linked planar-type walking robot was developed on the basis of the model of a semi-passive walking robot. An antagonistic actuation mechanism based on the human musculoskeletal structure was applied to the hip joint of the developed walking robot. The antagonistic actuation was realized by using motors and wires. A control algorithm utilizing the antagonism for walking motion was proposed and applied to the walking experiment by using the developed robot. The results of the walking experiment conducted using the proposed control algorithm are presented and discussed.**

***Index Terms*—biped walking robot, antagonistic actuation, semi-passive walking, walking experiment**

I. Introduction

The existing biped robots exhibit advanced motion performance, especially walking. The walking capability has been realized based on the two main technologies of actuation and feedback control. For example, in the cases of ASIMO [1] and HRP-4 [2], a harmonic gear mechanism and ZMP (zero moment point)-based control have been employed. These robots had succeeded in continuous walking, and to some extent, even in fast walking.

However, the energy efficiency associated with the walking motion of typical biped robots is known to be worse than that of humans [3]. Passive walking is considered a potential approach to solving the energy efficiency problem [4], [5]. The legs of a passive walking robot follow a pendulum-like motion by using gravitational energy, thus allowing the robots to walk continuously and stably. Therefore, passive walking robots can walk without any actuators and controls on shallow slopes with certain initial conditions. This implies that from the energy efficiency viewpoint, passive walking robots are superior to typical walking robots with ZMP-based control. However, passive walking robots cannot walk on horizontal surfaces because they have no actuators and controls. Semi-passive walking robots utilizing the pendulum theory with minimal number of actuators have been considered for walking on horizontal surfaces in previous works of research [6], [7]. This walking strategy realizes human-like walking based on passive walking.

Recently, much attention has been paid to mimicking human structure, especially the musculoskeletal structure and its antagonistic actuation. Humans can adaptively adjust elasticity of the musculoskeletal structure by controlling the corresponding muscle tension. Thus, various types of human motion, such as walking, jumping, and running, requiring different systemic stiffness, could be performed. In addition, walking energy efficiency has been reported to improve by using musculoskeletal structure-like design [8]. Biped robots with musculoskeletal structure have been developed as well [9], [10]. Previously, we introduced and analyzed the model of a 1-DOF antagonistic actuation unit with a musculoskeletal structure [11], [12]. Simulation of motion and experiments by using the proposed control method and the calculation were also performed.

Therefore, the goal of the present study was to apply the results of our previous research to the development of a biped walking robot. A semi-passive walking robot with antagonistic actuation was designed and developed. A control algorithm, utilizing the passive walking theory, was proposed and embedded into the developed robot. Performance was tested in walking motion experiments.

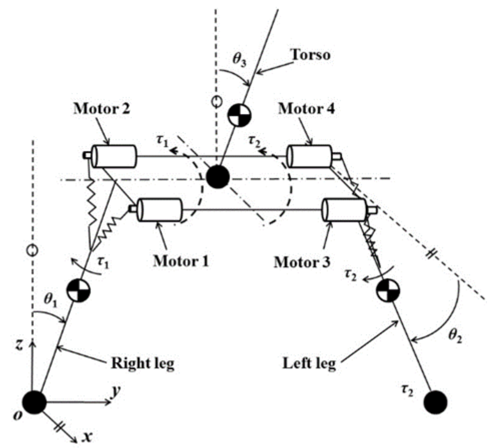

Figure 1. The model of the biped walking robot with antagonistic actuation

II. Development of a Biped Walking Robot

A. Model of a Biped Walking Robot

Fig. 1 shows the model of the walking robot. The model was derived based on the previously published

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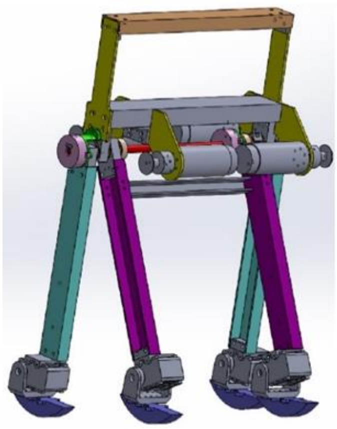
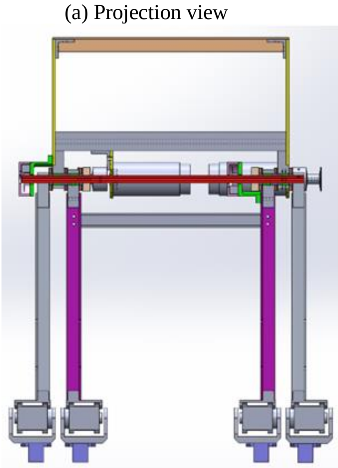
research [6], [7]. The model is a three-linked planar system comprising two legs and a torso. The control torques between the torso and each leg are generated by two antagonistic wires connected to the pulley of the DC motors on the torso link. The pulling force of each wire is generated by the torque for winding up the motor. It mimics the antagonistic actuation of the human musculoskeletal structure. The angles θ_1 and θ_2 are the right and left leg angles, respectively. The quantities τ_1 and τ_2 denote the control torques for both legs generated by the motors connected by the wires. The angle θ_3 is the pitch angle of the torso with respect to the vertical direction.

B. Mechanism Design of Biped Walking Robot

Fig. 2 shows the 3-D model of the robot designed in this research. The robot has two pairs of legs and one torso. To constrain the walking motion to the vertical planar space, each leg in Fig. 1 was designed as a pair of two parallel links. The inner legs were connected to each other by additional frame. The outer legs were fixed on the hip shaft. Therefore, both legs of each pair moved together, while leg pairs moved independently. The control torques for each pair of legs were generated by using two wires connected to the pulleys of the DC motors on the torso links. Thus, the left two motors were used for controlling the outer legs. the motors and the legs were connected by using wires as muscles.



(a) Projection view



(b) Sectional view

Figure 2. The 3-D model of the robot

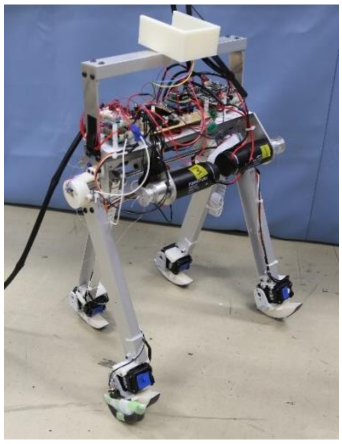
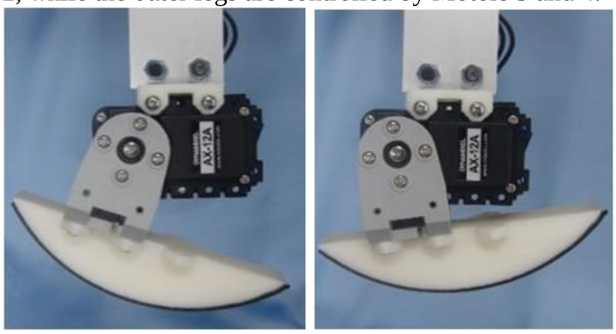


Figure 3. The experimental biped walking robot system developed in this research.

In the real robot in Fig. 3, θ_1 denotes the angle of the inner pair of legs, while θ_2 denotes the angle of the outer pair of legs. The control torques, τ_1 and τ_2, correspond to the angles. The inner legs are controlled by Motors 1 and 2, while the outer legs are controlled by Motors 3 and 4.



(a) During in landing state (b) During in swing state

Figure 4. The ankle part of the robot.

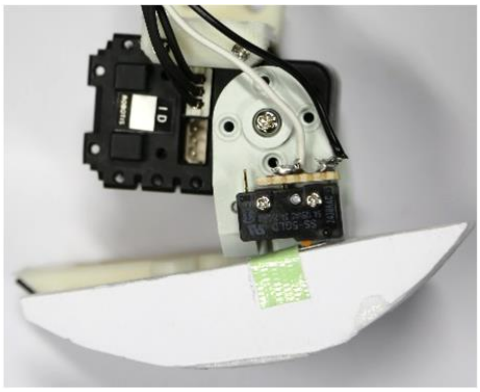


Figure 5. A Touch sensor on the foot

The foot of the model makes contact with the ground during swing motion because the lengths of all the legs are the same. Then, the contact becomes an obstacle for the walking motion. For avoiding contact, special foot mechanisms were used at the end points of all the legs in the actual robot system. By changing the foot angle, the length of the legs could be controlled. To change the robot feet angle, servo motors with embedded controllers were incorporated into the angle joints. Fig. 4 shows the ankle part of the robot. The ankle joints were used to lift the feet above the ground during the swing phase. When the legs were in the stance phase, the feet pointed downward, as shown in Fig. 4(a). On the contrary, when the feet of the swinging legs came closer to the ground, they were made to point upward by using the servo motors, as shown in Fig. 4(b), to prevent the feet from touching the ground. Touch sensors, developed in the present study, were used for determining whether the feet touched the ground. Fig. 5 shows a sample touch sensor. It is comprised of a limit switch and a trigger made of a foamed styrol plate. When the foot touches the ground, the trigger presses the limit switch and the landing of each leg can be detected.

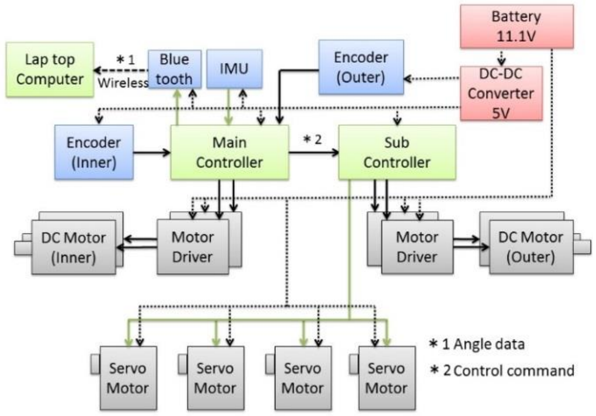


Figure 6. System configuration of the walking robot

C. *Configuration of Control System*

The system configuration of the developed robot system is shown in Fig. 6. This robot is controlled by two controllers. Two encoders were installed at the hip joints to measure the angles between both the leg pairs and torso. An attitude sensor (IMU: Inertial Measurement Unit) was installed on the robot's torso to measure the angle of the torso. The control torques were calculated using the main controller cased on the information from the sensors. For generating the torque of inner legs, Motors 1 and 2 were controlled by the main controller. Motors 3 and 4 for outer legs were controlled by the sub-controller, based on the commands from the main controller. The servo motors for changing the feet angles were also controlled by the sub-controller. The internal status, including the angles of the legs and the torso, was wirelessly sent to a laptop computer by using a Bluetooth module. The servo motors and motor drivers were supplied with voltage of 11.1 (V). the controllers, encoders, IMU and Bluetooth module were supplied with the voltage regulator of 5.0 volts.

III. Control Meshod

A. *Control of Walking Motion*

The fundamental control scheme for walking motion of this research is based on semi-passive walking [6], an extension of passive walking [4], [5]. The robot's walking motion is decided in four stages, according to the values of the touch sensors. Fig. 7 shows the stages of the experimental robot. The stages are as follows:

(a) The inner legs are in the stance stage and the outer legs are in the swing phase.
(b) The both legs are in stance stage and θ_1 is positive.
(c) The outer legs are in the stance phase and the inner legs are in the swing phase.
(d) The both legs are in stance stage and θ_1 is negative.

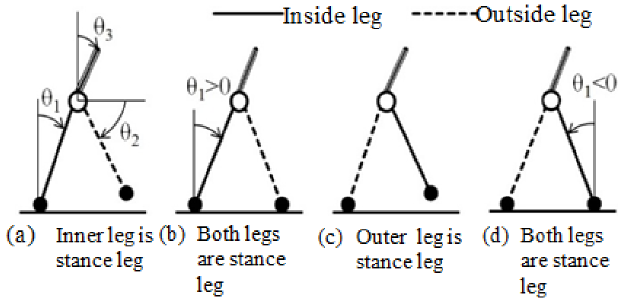


Figure 7. The stages of the experimental robot

Therefore, different control methods are applied according to these stages, as follows.

In the state (a), the control torques τ_1 and τ_2 are given as follows:

$$-\tau_1 - \tau_2 = k_3^p(\theta_{3d} - \theta_3) \tag{1}$$

$$\tau_2 = k_2^p(\theta_{12d} - \theta_{12}) \tag{2}$$

$$\theta_{12} = \theta_1 + \theta_2 \tag{3}$$

$$\theta_{12d} = \pi/2 \tag{4}$$

Here, $\tau_1$denotes the torque applied to the outer legs, τ_2 denotes the torque applied to the inner legs, k_3^p denotes the proportional gain, θ_{3d} denotes the desired angle of the torso, θ_{12d} denotes the desired angle of the outer legs, k_2^p denotes the proportional gain. In addition, the robot turns the feet of the inner legs downward and the feet of the outer legs upward.

In the stage (b), the control torques τ_1 and τ_2 are computed by (1) and the following equation:

$$\tau_1 = k_1^p(\theta_{12d} - \theta_{12}) \tag{5}$$

Here, k_1^p denotes the proportional gain. In addition, the robot turns the toes of the inner and outer legs downward.

In the stage (c), the control torques τ_1 and τ_2 are computed by (1) and (5). In addition, the robot turns the toes of the inner legs upward and the feet of the outer legs downward.

In the stage (d), the control torques τ_1 and τ_2 are computed by (1) and (2). In addition, the robot turns the toes of the inner and outer legs downward.

B. *Control of Walking Motion*

Each leg pair of the robot is controlled by two DC motors and wires; thus, the torque of the joints are generated by the torque of the four motors, and. They are computed by the following equations:

$$\tau_{1m} = \begin{cases} \tau_1 - \tau_p & (\tau_1 < 0) \\ -\tau_p & (\tau_1 > 0) \end{cases} \tag{6}$$

$$\tau_{2m} = \begin{cases} \tau_p & (\tau_1 < 0) \\ \tau_1 + \tau_p & (\tau_1 > 0) \end{cases} \tag{7}$$

$$\tau_{3m} = \begin{cases} \tau_2 - \tau_p & (\tau_2 < 0) \\ -\tau_p & (\tau_2 > 0) \end{cases} \tag{8}$$

$$\tau_{4m} = \begin{cases} \tau_p & (\tau_2 < 0) \\ \tau_2 + \tau_p & (\tau_2 > 0) \end{cases} \tag{9}$$

Here, τ_p is a preload torque for preventing wires from sagging and for changing the internal force in the antagonistic actuation.

IV. Walking Experiment

The developed robot system with the proposed method had been validated by performing a walking experiment on a horizontal surface.

A. Experimental Environment

Fig. 8 shows the environment of the walking experiment. This experiment was conducted on a horizontal surface. A linear frame and a belt connecting the robot to the bar were used for safety of the robot system. This configuration did not affect the walking motion. However, when the robot fell down owing to a walking motion failure, the robot was hung on the bar with a belt; thus, the configuration prevented the robot from collapsing on the ground.

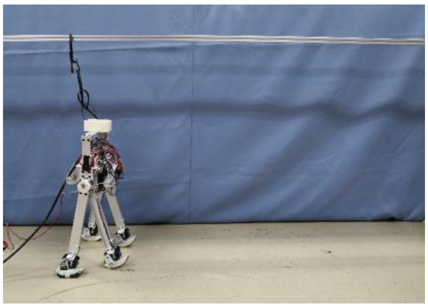


Figure 8. Experimental environment

B. Experimental Result

Fig. 10 shows experimental result. The figures, from (a) to (l) in Fig. 10, show the snapshot captured while the robot had been walking on the ground in the experiment. Fig. 9 shows the time history responses of the angles of both legs and the torso. The robot landed 4 times in this experiment.

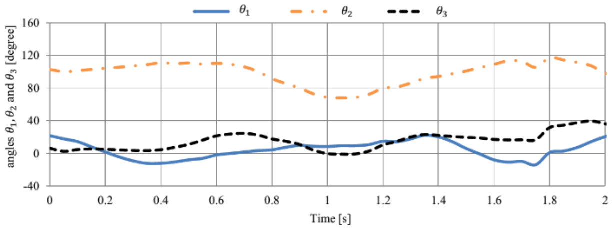
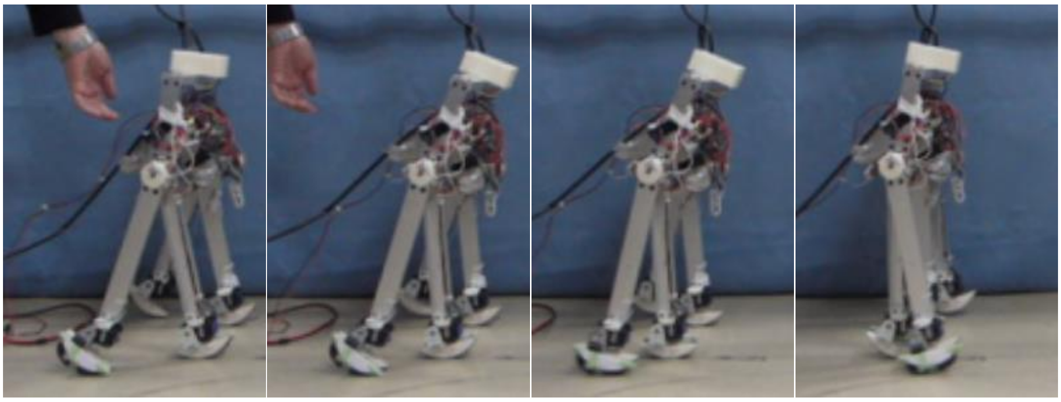
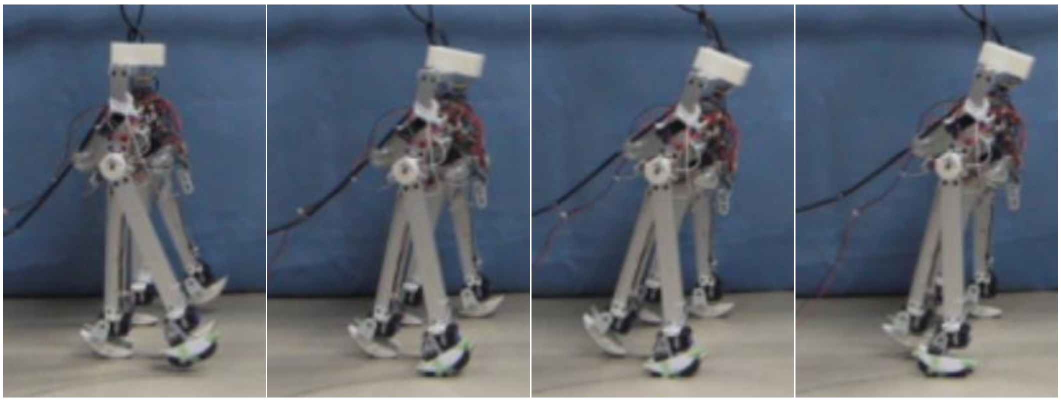


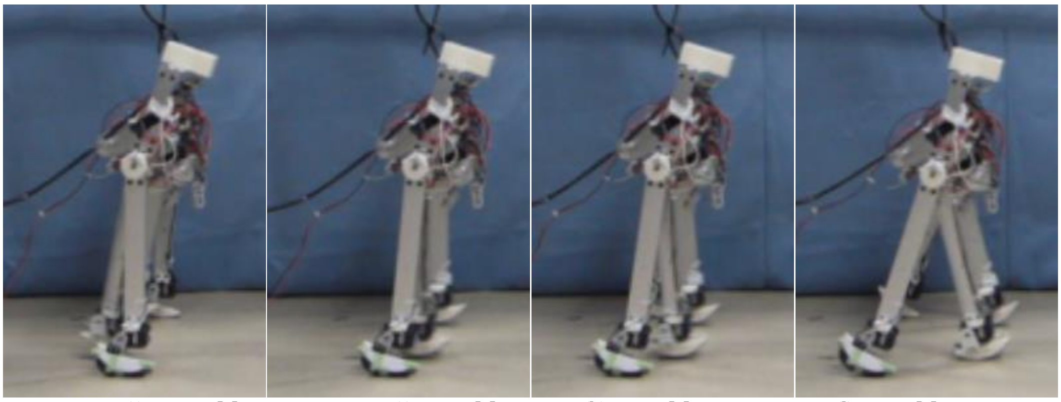
Figure 9. Temporal dynamics of the joints' angles for the robot walking with P control



(a) t = 0.43 [s] (b) t=0.60[s] (c) t=0.66[s] (d) t=0.84[s]



(e) t =0.93 [s] (f) t=1.20[s] (g) t=1.30[s] (h) t=1.40[s]



(i) t = 1.44[s] (j) t=1.49[s] (k) t=1.53[s] (l) t=1.63[s]

Figure 10. Experimental result of the robot walking

V. CONCLUSION

In this present study, we developed a semi-passive biped walking robot with antagonistic actuation. The walking experiment was conducted by using the control method proposed in the present study. We experimentally demonstrated that the developed robot with antagonistic actuation could walk on horizontal surfaces. Furthermore, the robot capability is similar to that of a previously developed robot with no antagonistic actuation [6].

For controlling the robot stiffness, a particular elastic wire such as Stiffness Adjustable Tendon (SAT) is needed for implementing the actuation mechanism [13]. Research efforts are underway for utilizing the stiffness adjustment capability for the motion control of biped walking robots.

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Takashige Yano graduated from the Ehime University, in 2014 with a B.S. degree in Mechanical Engineering. Currentry, he is M.S. student of Gradeate School of Science and Engineering, Ehime University, Japan.
During the four years of undergraduate study at the Ehime Universisy, he successfully completed all the requirements from the department of mechanical engineering. During the first year of M.Sc. study, he completed his course work and started his thesis work with Dr. J.H. Lee about a walking robot with antagonistic actuation.

Jae Hoon Lee received the B.S. degree in mechanical and automatic control engineering from Korea University of Technology and Education, Cheonan, Korea, in 1996, and the M.S. and Ph.D. degrees in electric, electrical, control and instrumentation Engineering from Hanyang University, Ansan, Korea, in 1998 and 2003, respectively.
From 2004 to 2006, he was a Postdoctoral fellow at the Intelligent Robot Laboratory, University of Tsukuba, Japan. From 2007 to 2008, he was a JSPS fellow with the Ubiquitous Functions Research Group, Intelligent Systems Research Institute, AIST, Japan.
During He is currently an Associate Professor in the Department of Mechanical Engineering, Graduate School of Science and Engineering, Ehime University, Matsuyama, Japan. His current research interests include the design and control of bio-inspired robotic systems, the collaborative navigation of mobile robot in daily environment, and the development of rotorcraft systems.

Shingo Okamoto was born in April 1959 in Japan. He took Bachelor of Engineering in 1982 and Master of Engineering in 1984 from Ehime University. He also took Doctor of Engineering in 1992 from Tokyo Institute of Technology.

He had been doing a research as a Visiting Scientist in Massachusetts Institute of Technology for the period from 1998 through 1999. He is interested in Robotics, Intelligent Systems, Computational Mechanics and Medical Engineering. Then he is Professor of Mechanical Engineering of Ehime University from 2008 to the present.

Prof. Okamoto is a member of JSME (The Japan Society of Mechanical Engineers, RSL (The Robotics Society of Japan), SICE (The Society of Instrument and Control Engineers), JSCES (The Japan Society for Computational Engineering and Science) and JSCAS (Japan Society of Computer Aided Surgery)