Development of a Biped Walking Robot Actuated by a Closed-Chain Mechanism

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Abstract : We developed a new type of human-sized BWR (biped walking robot), named KUBIR1 which is driven by the closed-chain type of actuator. A new type of the closed-chain actuator for the robot is developed, which is composed of the four-bar-link mechanism driven by the ball screw which has high strength and high gear ratio.

Each leg of the robot is composed of 6 D.O.F joints. For front walking, three pitch joints and one roll joint at the ankle. In addition to this, one yaw joint for direction change, and another roll joint for balancing the body are attached. Also, the robot has two D.O.F joints of each hand and three D.O.F. for eye motion. There are three actuating motors for stereo cameras for eyes. In all, a 18 degree-of-freedom robot was developed.

KUBIR1 was designed to walk autonomously by adapting small 90W DC motors as the robot actuators and batteries and controllers are on-boarded. The whole weight for Kubir1 is over 90Kg, and height is 167Cm. In the paper, the performance test of KUBIR1 will be shown.

Keywords : Biped Walking Robot, Ball Screw, Four-bar-link Mechanism

1. INTRODUCTION

As an early stage of the research on the driving mechanism, hydraulic power system was applied to drive legs of the BWR by Takanish[1]. However, since the hydraulic system was so heavy, bulky, and difficult to maintain, servo motors with speed reducer have been most widely used to drive leg joints. The harmonic drive is the most widely used speed reducer since its gear ratio is so high and compact despite of light weight. But, despite of high gear ratio, it is not stiff enough to actuate leg joints of BWRs. To compensate for the gravity and to increase the driving torque, a spring mechanism was devised and applied to leg joints by Yamaguchi[2]. Despite of these approaches, the driving torque was not improved enough to actuate the BWRs. A biped robot to aim at having anthropomophing characteristics was developed by Espiau[3], whose joints are actuated by the rod crank system composed of screw nuts. One of succeeding ways in developing human-sized BWRs is to devise actuators which are small and light but have high stiffness and high gear ratio.

Without strong joint actuators, the BWR has very limited walking ability. Shih[4] developed a small BWR which 800 (mm) high and seven D.O.F. including one prismatic balancing joint. In 1998, Yamaguchi[2] developed small nine D.O.F. BWR which is 1405(mm) high and had 0.12(m/sec) walking speed. So far, the most developed human-sized BWRs are the Asimo and P3 robots. The P3 BWR was developed by Hirai[5] at the Honda company LTD., and smaller but more improved version is Asimo. They are developed as humanoids, and walk in most similar manner with human beings. The speed reducer for leg joints is specified as the harmonic drive, but the driving mechanism information such as the capacity of actuating motors, details of the speed reducers, and control algorithm is not open yet.

We developed a 18 D.O.F human-sized BWR, which is actuated by a novel joint actuator using four-bar-link driven by the ball screw. In this paper, we present the structure, the actuating mechanism, the composed controller and driver, and the walking performance. In section 2 of the paper, four-bar-link mechanism actuated by the ball screw is analyzed. In section 3, the kinematic mechanism of the BWR actuated by the proposed joint actuators is shown. In addition to this, the mechanical structure and control systems including the motor driver and motion control system are presented in section 4. Finally, through walking tests of the actuator and the robot, performance results are shown and discussed.

2. MECHANISM OF THE JOINT ACTUATORS

We developed the lower body of the humanoid robot, which has two legs and a trunk, and two arms. Each leg has the pelvis, knee, and two ankle joints. The leg joints of the BWR moving along the pitch direction are composed of ankle, knee, and pelvis joints as shown in Fig. 1. The joint actuators are composed of the four-bar-link mechanism whose one link is the ball screw actuator.

2.1 Four-bar-link mechanism for the ankle joint

The ankle joint is a part of the four-bar-link mechanism, which is rotated by driving the ball screw along the translational direction. The structure of the four-bar link mechanism is shown in Fig. 2, where b_1 represents a connecting bar between the ankle joint and the knee joint, and c_1 represents another bar composed of the foot. The ankle joint β_1 rotates as the position of the ball screw d_1 moves in the translational direction. The relation between the ankle joint and the position of the ball screw can be expressed using the trigonometric function. As shown in Fig. 2, The rectangle is divided into two triangles, and Cosine rule in the trigonometric function is applied to both triangles to find the relation between β_1 and d_1. The equation showing the relation is expressed as

$$. \quad d_1^2 = A_1 + B_1 \cos\beta_1 + C_1 d_1 \qquad (1)$$

where $A_1 = b_1^2 + c_1^2 - a_1^2$

$B_1 = -2 b_1 c_1, \quad C_1 = 2 a_1 \cos \alpha_1$

where the length of links a_1, b_1, c_1, and the angles α_1 and N_1 are design parameters and all known. Solving Eq. (1) with respect to the displacement of the ball screw d_1 yields

$$d_1 = \frac{C_1 + [C_1^2 + 4(A_1 + B_1 \cos\beta_1)]^{0.5}}{2} \qquad (2)$$

By differentiating d_1 with respect to time, the kinematic relation is obtained as

$$\dot{d}_1 = -[C_1^2 + 4(A_1 + B_1\cos\beta_1)]^{-0.5} B_1 \sin\beta_1 \dot{\beta}_1 \qquad (3)$$

Using the relation $q_1 = \pi - \beta_1$, the kinematic relation between $\dot{q}_1$ and $\dot{\beta}_1$ is expressed as

$$\dot{\beta}_1 = \dot{q}_1 = R_{11} = \frac{[C_1^2 + 4(A_1 + B_1\cos\beta_1)]^{0.5}}{B_1 \sin\beta_1} \dot{d}_1 \qquad (4)$$

2.2 Four-bar-link mechanism for the knee joint

The four-bar-link mechanism applied to the knee joint is shown in Fig. 3, where b_2 represents a connecting bar between the knee joint and the pelvis joint, and d_2 represents the translational displacement of the ball screw. The relation is shown between d_2 and β_2 which is the revolution joint of the knee as

$$d_2 = \frac{C_2 + [C_2^2 + 4(A_2 + B_2 \cos\beta_2)]^{0.5}}{2}$$

(5)

where $A_2 = b_2^2 + c_2^2 - a_2^2$

$B_2 = -2 b_2 c_2, \quad C_2 = 2 a_2 \cos\alpha_2$

where the length of links a_2, b_2, c_2, and the angles α_2 and N_{2k} are all known design parameters. As shown in Fig. 3, the relating equation between q_2 and d_2 is obtained as

$$\dot{d}_2 = -[C_2^2 + 4(A_2 + B_2\cos\beta_2)]^{-0.5} B_2 \sin\beta_2 \dot{\beta}_2 \qquad (6)$$

Also, using relation $q_2 = \pi - \beta_2 - N_{2k}$, the kinematic relation between $\dot{\beta}_2$ and $\dot{d}_2$ is obtained as

$$\dot{\beta}_2 = -\dot{q}_2 = R_{12} = \frac{[C_2^2 + 4(A_2 + B_2\cos\beta_2)]^{0.5}}{B_2 \sin\beta_2} \dot{d}_2,$$

(7)

Similar mechanism is applied to the pelvis joint

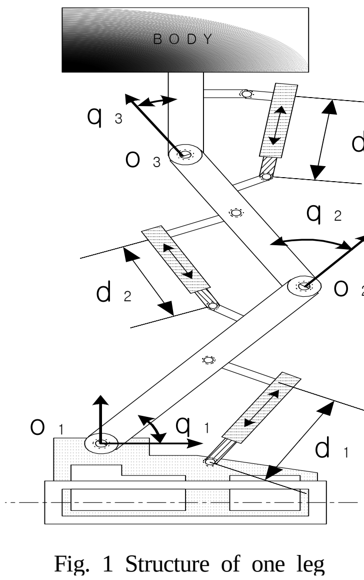

Fig. 1 Structure of one leg

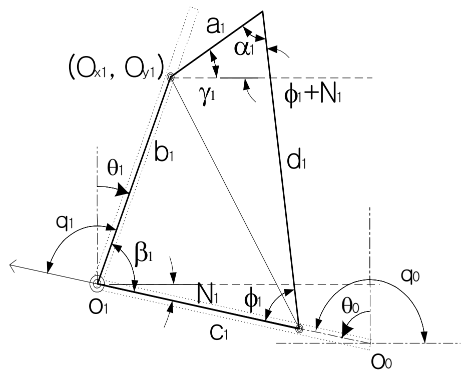

Fig. 2 Geometric configuration of the ankle joint

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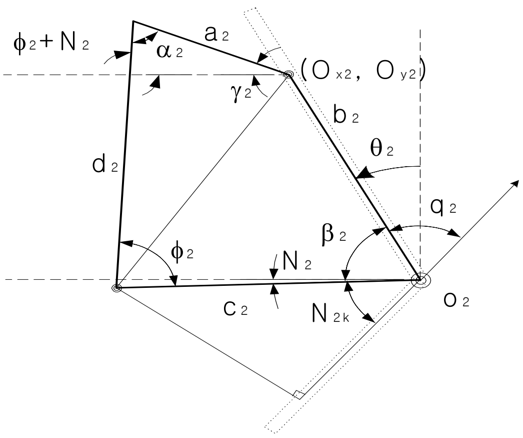


Fig 3. Geometric configuration of the knee joint

Pic. 1 Four-bar-link mechanism actuated by ball screw

3. THE DESCRIPTION OF THE ROBOT

3.1 The structure of BWR

The external appearance of the BWR is shown in Pic. 2, and its structure is composed as

■ Six leg joints actuated by the four-bar-link mechanism

■ Two roll joints for ankles actuated by the motors attached with the speed reducers

■ Four arm joints actuated by motors attached with the speed reducers

■ 3 D.O.F. active stereo vision system actuated by three DC motors

The six joints are designed for pitching motion, and the two joints for ankles are designed for balancing the weight of the robot in the roll direction. The arms were designed to do manual operation and to help balancing pitching motion during walking motion. The kinematic structure of the BWR is shown in Pic. 2.

Table. 1 specifications of the KUBIR actuators

Parts / Item	Rights and Left legs				Balancing weight	
	foot (Roll)	ankle	knee	pelvis	pitch	roll
DC Servo Motor[W]	90	90	90	90	90	90
Gear Ratio	126:1	1:1	1:1	1:1	126:1	126:1
Encoder Resolution	2000	2000	2000	2000	2000	2000
Lead of Ball Screw(mm/rev)		5	5	5		

The height of KUBIR is 1670(mm). The motor to actuate the ball screw of the four-bar-link is DC motor with the increamental encoder. The specification of the actuation motors and ball screws for the BWR is shown in Table 1.

Pic. 2 12 D.O.F BWR

4. CONTROL SYSTEM

The BWR was designed for autonomous walking such that it is boarded with the controller, driver, and batteries. To reduce the weight of the robot, we used small 90W DC motors as driving motors for the four-bar-link joint actuator, and we also developed DC motor drivers and I/O(input-output) interface system. We constructed the whole control system except the motion control board in order to reduce the size of the control system. The structure of the developed control system is shown in Fig. 5 and its picture is shown in Pic. 3. The constructed system are composed as

- DC servo motor driver
- Commercial motion controller (MMC-PV8)
- Main control system
- System I/O interface.

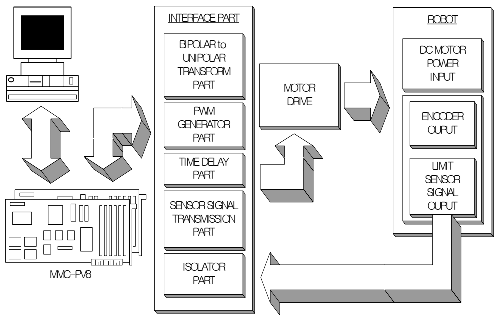
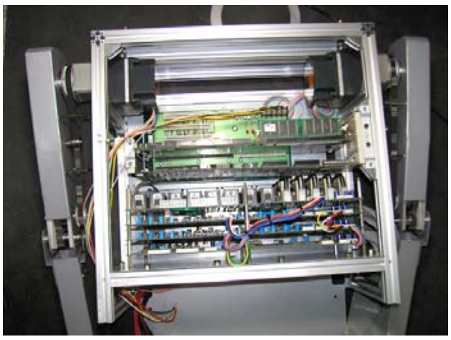


Fig. 4 Block diagram of the total control system



Pic 3. The controller of the BWR

To reduce the size and weight of robot, we constructed the motor driver by using FET power devices and related electronic devices. The driver can supply the power to rotate the motor in bi-direction and has capability of limiting over-current flow to protect motors by employing Hall sensors.

The robot has twelve joints composed of eight leg joints and four arm joints. All the joints are designed to be active joints such that the robot requires twelve actuators composed of motors and drivers. To control them, two motion controllers named MMC(multi-motion control) board was used. The board adopts a DSP processor which can make high speed calculation and has a PIDF (Proportional-Integral-Derivative-Feedforward) control loop.

As a main control system for the biped, we used the Pentium IV on-board computer which boards the MMC motion controller on it. The main control system edits control programs, gain setting of the PIDF control algorithm in the motion controller, planning of joint trajectories, and monitoring the motion of the robot.

For the communication among the MMC board, the motor, and drivers, we constructed the I/O interface system. The structure is shown in Fig. 4 and Pic. 3 where the bipolar-to-unipolar transform part generates the velocity and direction signal for the motor. The pulse width modulation (PWM) generator part creates the PWM signal. The I/O interface system includes a time delay circuit and a photo-isolator circuit. The time delay circuit protects the driver circuit devices from over-current flows by delaying the input over-current flow for a short time for bi-directional power change. The photo-isolator circuit filters out noises and cuts off high reverse currents. In the I/O interface system, the sensor signal transmission circuit transfers encoder and limit sensor signals to the motion controller.

5. PERFORMANCE TESTS

The height of the BWR we developed is 1670(mm). It weighs 90 Kg and has eight joints in legs and four arm joints. A four-bar-link actuator was developed to actuate the joint of the BWR and was applied to six pitching leg joints. For arm joints, DC motors with speed reducer were applied.

We performed walking tests of the BWR where reference data for the walking joint trajectories were obtained from the data of the human walking motion using the motion capture system. To obtain reference walking data, a human being wears the motion capture system with rotary potentiometers as shown in Pic. 4. The reference walking data were partially exploited as input data. For one period walking, a number of reference tracking joint angles were given. One period of walking motion is shown in Pic. 5. A slow walking test was performed such that one cycle time of a gate for both legs took 7 seconds, and a gait width was 50 cm. As shown in Pic 5, the BWR could successfully walk along the specified trajectory.

One of the important purposes of the test was to identify the tracking ability of the joint actuator weighing 90 Kg using the developed small-sized joint actuators. Fig. 5 shows the trajectory tracking of ball screws along desired trajectories. Figs. 6 show trajectory tracking errors of all the joints. As shown in Figs, joint actuators show good performance with small tracking errors. Throughout the test, all the system including motor driver, I/O system, and mechanical system performed well.

The developed robot is not perfectly designed as anthropomorphic such that it can not walk fast and stably enough as human being does. However, despite of the condition, the BWR showed stable walking ability. This represents that the proposed four-bar-link joint actuator of the robot shows the capability to actuate the heavy BWR by using the small 90W motor.

Pic. 4 The motion capture system

6. CONCLUSION

We developed a 18 D.O.F. BWR which is actuated by a new joint actuator composed of the four-bar-link mechanism. The weight of the BWR is 90Kg and the height is 1670mm. The whole mechanical and electronic system was constructed except the motion controller. According to walking performance tests, despite of the small-powered actuating motors, the proposed joint actuators could successfully drive the heavy robot along the specified trajectory. This indicates that the proposed actuator has enough stiffness and torque transmission ability. Through the basic walking tests, we obtained experimental data of the stable walking motion of the BWR, and found that the proposed actuator has high transmission ability and that the BWR including the proposed actuator has a capability of carrying heavier weight and of faster walking motion.

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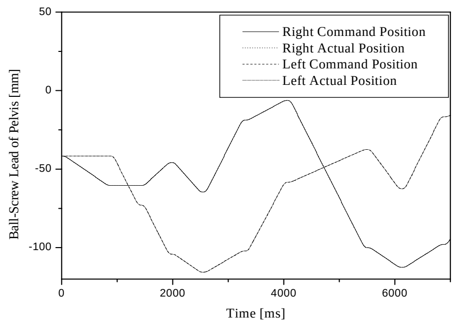


Fig. 5 Walking path of pelvice joint

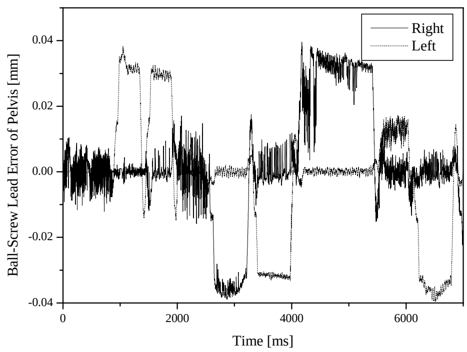
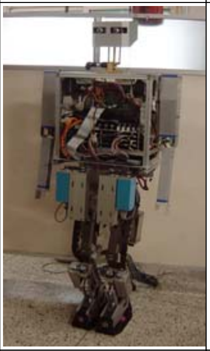
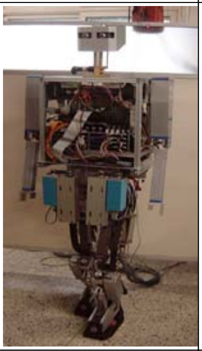
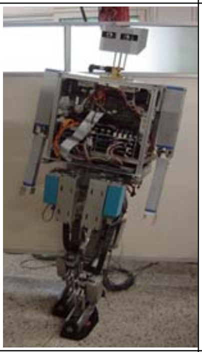
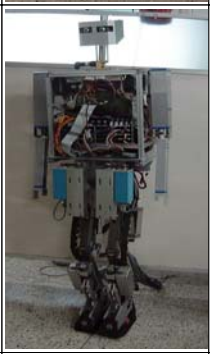
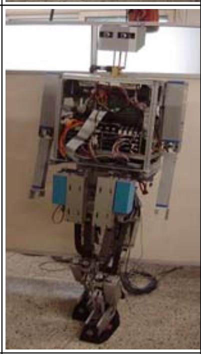
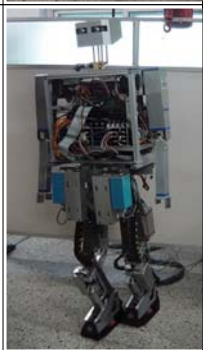
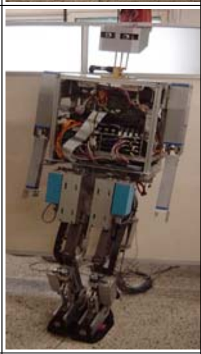
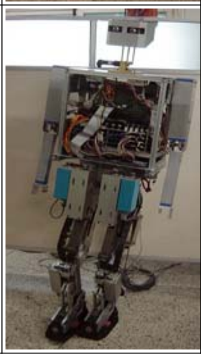


Fig. 6 Tracking error of pelvise joint

Steps	Walking posture	Steps	Walking posture	Steps	Walking posture
STEP 1		STEP 6		STEP 11	
STEP 2		STEP 7		STEP 12	
STEP 3		STEP 8		STEP 13	
STEP 4		STEP 9		STEP 14	
STEP 5		STEP 10		STEP 15	

Pic. 5 Walking perfomance test