# Development of a Bio-mimetic Quadruped Walking Robot with Waist Joint

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**Abstract**: This paper presents a novel bio-mimetic quadruped walking robot with a waist joint, which connects the front and the rear parts of the body. The new robot, called ELIRO-1(Eating LIzard RObot version 1), can bend its body while the legs is transferred, thereby increasing the stride and speed of the robot. The waist-jointed walking robot can move easily from side to side, which is an important feature to guarantee a larger gait stability margin than that of a conventional single rigid-body walking robot. We design the mechanical structure of the robot, which is small and light to have high movability and high degree of human friendship. In this paper, we describe characteristics of the waist joint and leg mechanism as well as the analysis using ADAMS to select appropriate actuators. In addition, a hardware and software of the controller of ELIRO-1 are described.

**Keywords:** Quadruped walking robot, waist-joint, articulate spine, pantograph

## 1. INTRODUCTION

Robots are now being utilized in almost field, including entertainment, education, medical treatment, and hazardous environments. Imitating the action or form of a particular animal allows for the development of special purpose robots[1-2]. The development of bio-mimetic robots has become the main focus and challenge of new robot development. Most recently developed legged robots are either humanoid that imitate humans or quadruped walking robots that imitate animals.

In the natural world, vertebrates exhibit superior mobility in an irregular terrain, such as uneven ground or slopes since they have a waist joint or an articulated spine. Furthermore, these animals have a high stability and can move fast, because they use their spine effectively. For example, the leg length of a crocodile or lizard is short compared with their body size, yet these animals are able to move fast based on bending their body to the right and left using a waist joint, which is an important aspect of animal locomotion. In contrast, a conventional quadruped walking robot is usually composed of a single rigid body[3-5], making it impossible to embody a gait that uses a waist, like in an animal. In case of walking using a waist joint, the reachable area of the tip of the leg is so widened that both the stability and the walking speed increase[6]. Plus, robots with a waist joint are more adaptable to irregular environments. There has been a few robots with articulated spine such as GEO[7] and SQ43[8].

Accordingly, in this paper, we propose a novel quadruped walking robot with a waist joint based on the model of a lizard, called ELIRO-1(Eating LIzard RObot version 1). The ELIRO-1 is not only a quadruped robot but also an eating robot. In this paper, we will describe only about the part of the quadruped robot with a waist joint. The actuator, batteries, and controller are equipped on the ELIRO-1 to enable autonomous walking. The mechanical structure is also kept small and light to enhance the mobility and a sense of intimacy with human.

## 2. DESIGN CONCEPT AND BASIC FEATURES

Basically, the ELIRO-1 is modeled after a lizard. The robot has four legs and 1-dof waist joint with which locomotion on even terrain is only considered. The standing height of the robot is designed to be low from a model of a lizard. In addition, the size of the robot is kept as small as possible to mitigate the complexity of structure and control. The size of the robot was determined in consideration of the contents of the body(eating mechanism of the ELIRO-1, controller, and batteries) and the possibility of manufacturing.

On the other hand, the walking robot has a lot of actuators to drive legs. A walking robot must carry its own actuators while it moves. Therefore, we must consider the ratio of the output torque to the weight of motor. In order to use of a waist joint efficiently, the kinematics of legs should be investigated to guarantee the waist joint movement and also the weight balance between the upper body and the lower body should be considered.

We designed a quadruped walking robot based on above design considerations. We adopted RC (Radio Control) servo motors as actuators for legs, which is easy to control and needs only a simple interface hardware. In case of a RC servo motor, its maximum operation range is usually from – 90 degrees to +90 degrees. This limitation should take into account in the design of the mechanism.

From an energy efficiency aspect, it is preferable for a leg structure to reduce the power consumption by gravity. It is already known that the use of pantograph mechanism for legs is efficient to reduce the energy consumption and to have good rigidity, less inertia, and a simple drive system[9]. Thus, we adopted a pantograph structure for the legs.

Fig. 1 represents a 3-D design drawing of the quadruped mechanism of the ELIRO-I. The developed prototype of the quadruped mechanism is shown in Fig. 2. The mechanism has 13 DOF(Degree of freedom) including 3 DOFs for each leg and 1 passive DOF in the waist joint. The weight is 6kg and the height of the body is 250mm. Two packs of Ni-MH batteries are used. Each battery pack can supply 6V in voltage output and 4800mAh in capacity. Table 1 shows the specification of the quadruped walking robot.

Table 1 Specification of the quadruped walking robot.

| | |
|---|---|
| Dimensions | 450L x 330W x 250H (mm) |
| Weight | 6 kg (without battery) |
| Actuator | HS-945MG x 8 EA<br>HS-815BB x 4 EA |
| Power Source | DC 6 [V] (for motors)<br>DC 5 [V] (for controller) |

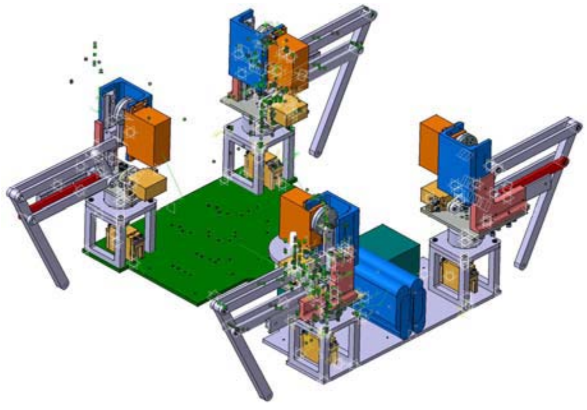

Fig. 1 3-D design drawing of the quadruped mechanism of the ELIRO-1.

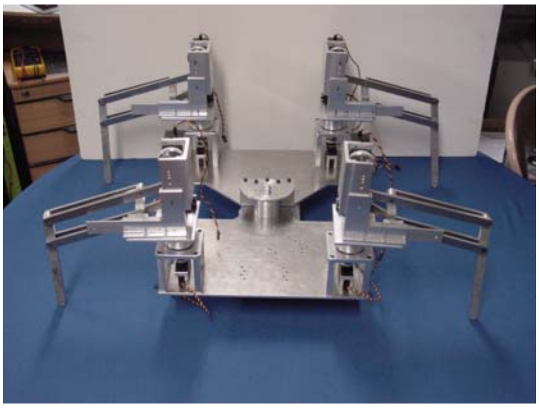

Fig. 2 Quadruped mechanism of the ELIRO-1.

## 3. MECHANICAL COMPONENTS

### 3.1 Waist part

The waist-jointed body is divided into the upper and lower body. In the current design, the waist joint has only 1-DOF so that it can rotate horizontally. The angle of waist joint formed by the upper and lower body is divided into the upper angle and lower angle with respect to the moving direction of the robot. The position of the 1-DOF waist joint, the upper angle, and the lower angle are uniquely determined by four positions of the hips of the robot. The positions of the hips in turn fully depend on the movement of legs. This implies that no actuator is needed at the waist joint. Thus, the 1-DOF waist joint is designed as a passive joint.

The mechanism of waist joint is designed in consideration of an appropriate range of angle and less deflection between the upper body and lower body. The designed range of rotating angle of the waist joint is from -90 degrees to +90 degrees. The waist joint is constructed by a thrust needle bearing, NKXZ9 and hard lock nut(see Fig. 3).

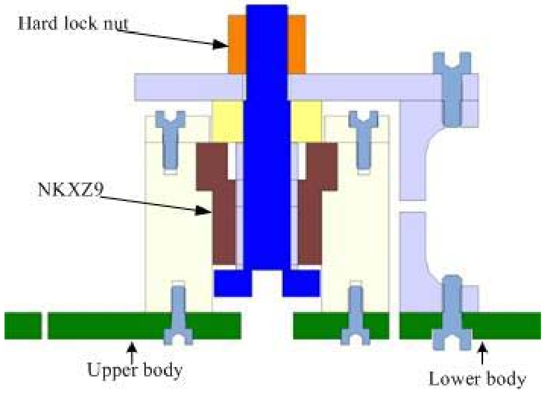

Fig. 3 Cross-sectional view of the waist joint.

### 3.2 Leg part

A leg is a 3-DOF mechanism which is composed of 2-DOF pantograph with translational joints for horizontal and vertical movements and one rotational joint with which a leg can rotate around its vertical shaft. There are several alternative devices to implement the translational movement such as a slider–crank mechanism, rack-pinion, belt drive, and ball screw. A ball screw is massive, and the rack-pinion and belt drive are complex. Yet, a slider-crank mechanism has several merits; less friction loss, small size, light weight, low manufacturing cost, easy to adjust. Thus, a slider-crank mechanism is selected as the leg-driving method for the robot.

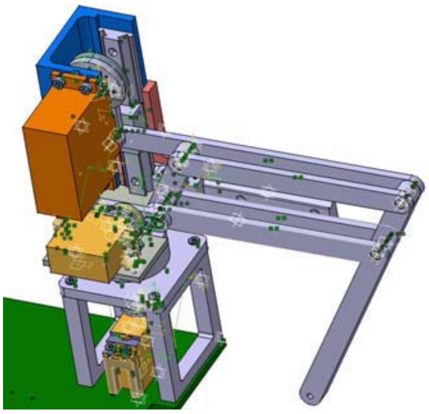

Fig. 4 3-D design drawing of a leg.

As shown in Fig. 5, the length of the link **a** and **b** are 5cm and 15cm, respectively. Thus, the pantograph ratio is 3:1. The maximum width and height of reachable volume of a leg is 40cm and 30cm, respectively. The actual allowable range of a leg movement is restricted to an area of 16cm in width and 6cm in height according to the structural restriction and a set of preferred motion of the robot.

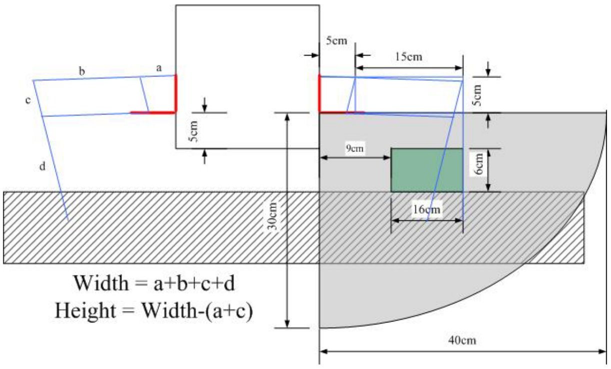

Fig. 5 Reachable volume of a leg.

## 4. ANALYSIS OF MECHANICAL DESIGN

To verify the mechanical design and to choose appropriate actuators, we have performed dynamics analysis using an automatic dynamic analysis program ADMAS v12. For the simulation, the model of the robot divides into body, head, and parts of leg. The robot model has all joints except the waist joint and the parameters of the size and weight is chosen as similar as possible with the real robot to be manufactured. A contact and an attrition phenomenon between the foot-tip and the ground are not considered.

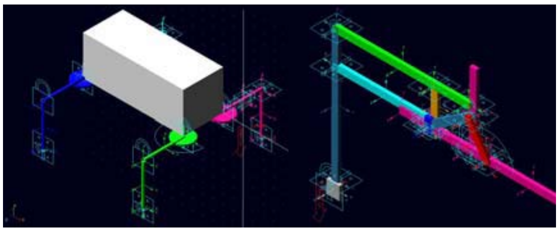

Fig. 6 Model of the body and leg using ADAMS.

When a robot walks with a static gait, more than three legs support the body while one leg is lifted. If the weight of the body is evenly distributed on each supporting leg, one leg should support only one third of it. However, the distribution of the weight of the body varies as the robot walks. Thus, in consideration of various kinds of gaits, it is reasonable that half of the weight of the body assumes to be loaded on a support leg for a simulation of selection of actuators.

Based on the expectation that the total weight of the robot will be less than 10kg, a load of 5kg is considered as the maximum load of one supporting leg. Fig. 7 and Fig. 8 represent simulation results when the loads of a supporting leg are 0kg, 1kg, and 5kg. Each graph is a torque trajectory of each joint during each slide-crank mechanism sweeps over its whole working range. Each graph is periodic according to the cyclic motion of the slide-crank mechanism.

Fig. 9 is represents the simulation result that the body moves forward and backward by driving rotational joint around the vertical axis. Two graphs in Fig. 9 is torque trajectories for the weight of the body of 10kg and 20kg.

Using these simulation results, we have selected motors for each axis. The x-axis motor and z-axis motor move the body in horizontal and vertical direction, respectively. The y-axis motor can rotate a leg around the vertical axis.

To meet the maximum torque requirement, we have selected RC servo motors, HS-945MG and HS-815BB of Hitec. The HS-945MG and HS-815BB have the maximum torque of 11kgcm and 23kgcm, respectively. The HS-945MG is used for x-axis and y-axis driving. The HS-815BB is used for z-axis driving. The RC motors are suitable for small-sized robots since its ratio of the torque output to the weight is high and the controlling circuit is rather simple.

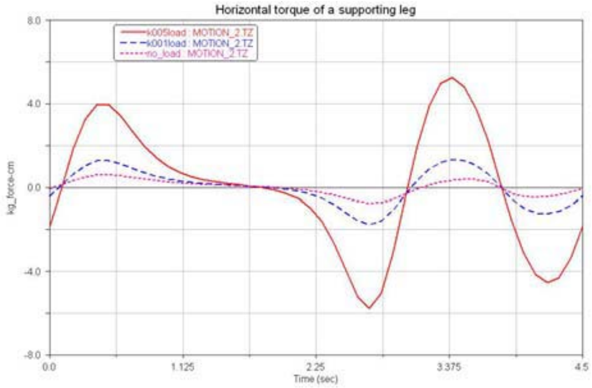

Fig. 7 Torque trajectories of horizontal motion of a supporting leg.

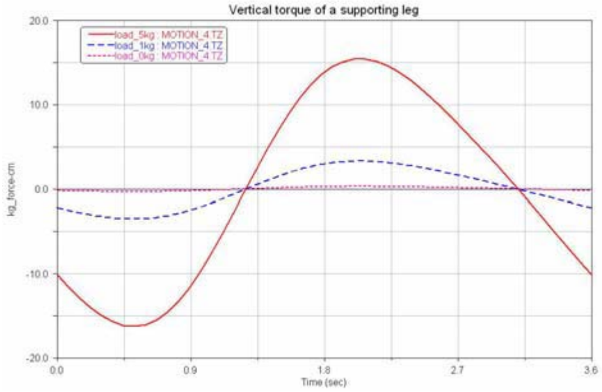

Fig. 8 Torque trajectories of vertical motion of a supporting leg.

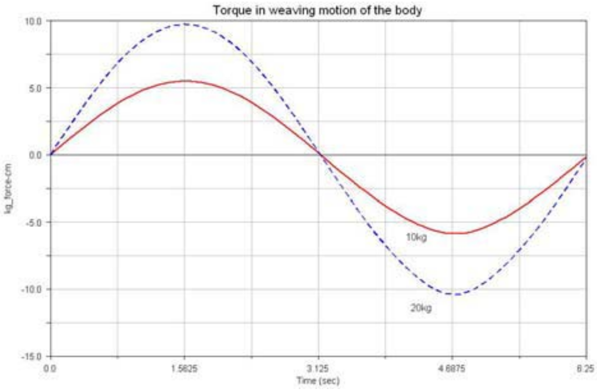

Fig. 9 Torque in weaving motion of the body.

## 5. CONTROL SYSTEM

5.1 Hardware of control system

The overall diagram of control system is as shown in Fig. 10. The control system consists of a microcontroller unit and a

PWM signal generating unit. The microcontroller unit consists of a 32-bit digital signal controller, TMS320F2812 of TI, an external memory, and a power regulator part. The PWM signal generating board is based on a FPGA, XCS40XL of XILINX.

Microcontroller unit takes in charge of gait planning and generation of command data to control RC servo motors. A RC servomotor is driven by a PWM signal with a refresh cycle of 20msec. It is not suitable that the control signals for twelve RC motors are generated by software on the microcontroller. Thus, we have designed special-purpose PWM signal generating board for control of twelve RC motors.

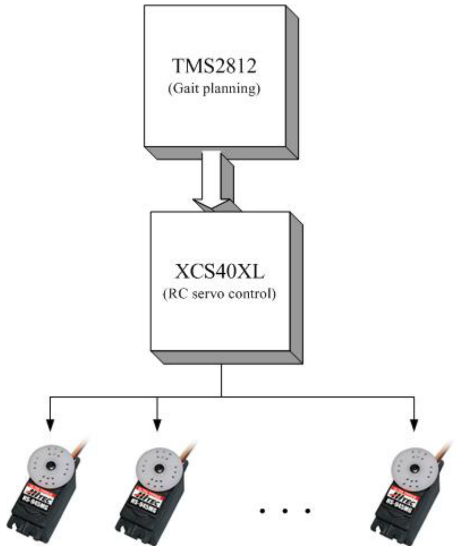

Fig. 10 Diagram of control system.

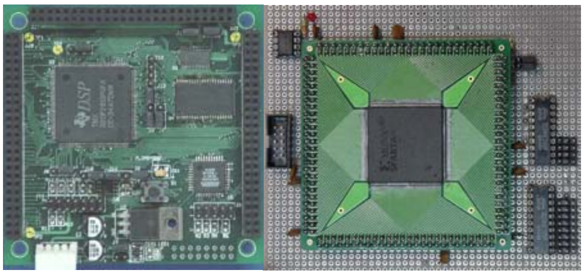

Fig. 11 Photos of hardware boards of control system.

5.2 Software of control system

The gait of the robot is planned as follows. For a given command from a user or a task, the mode of motion is chosen. In case of walking mode, a set of gait parameters such as leg sequence and stride is selected from a predetermined table. The hip position and the parameters of the waist joint are calculated. Then, the trajectory data of each leg is calculated by solving inverse kinematics. The angles for each motors is passed to the motor control part for every control period. In case of action of standing up and sitting down, all legs move the body upward or downward.

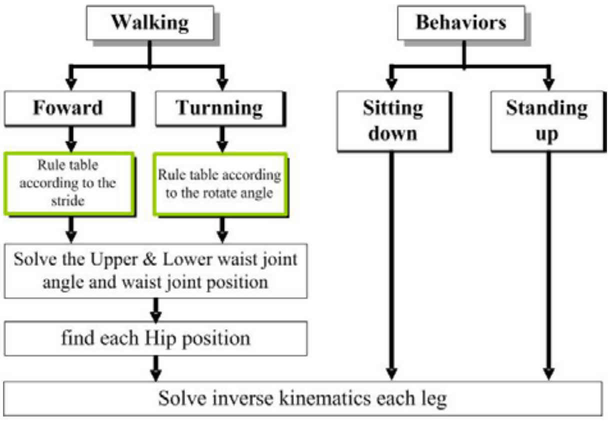

Fig. 12 Gait planning sequence.

A gait sequence is shown in Fig. 13. Basically, the implemented gait of the ELIRO-1 is a discontinuous gait that the center of gravity of the robot moves only in a four-leg-supporting phase, i.e., a leg moves forward while the body stops. Before a leg is lifted, the body is bent to enlarge the stroke of the leg. The legs swing in the order of rear-right leg, front-right leg, rear-left leg, and front-left leg.

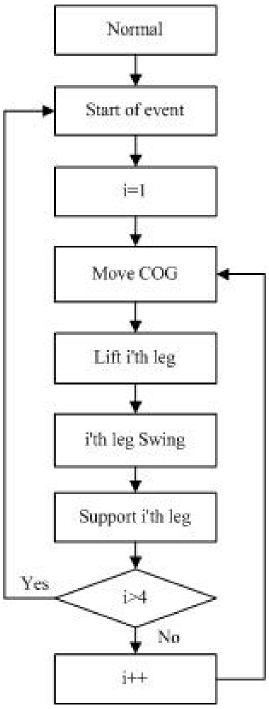

Fig. 13 Flowchart of a static walking.

## 6. CONCLUSION

In this paper, we proposed a novel bio-mimetic quadruped walking robot (ELIRO-1) with a waist joint which allows the body to be bent while a leg is transferred. Owing to the waist joint, both the stability and the walking speed increase. We described about details of the prototype robot including the waist joint and leg mechanism. To select appropriate actuators, the dynamic analysis using a model of the robot was performed. In addition, a hardware and software of the controller of the ELIRO-1 are described.

## ACKNOWLEDGMENTS

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