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Development of a Hexapod Robot focusing on Leg Compliance

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Abstract

In this paper, a hexapod walking robot with a structural compliance mechanism is presented. In general, conventional walking robots have less mobility, while they are operated in particular rough terrain. One of the main reasons is that their body structures have high stiffness. However, insects, especially a cockroach, can accomplish fast locomotion everywhere, thanks to the flexible body compliance mechanisms derived from their musculoskeletal attributes. According to this, we developed a hexapod walking robot by focusing on the structural compliance mechanisms.

Key Words: biomimetic hexapod robot, mechanical compliance

1. Introduction

The workspace of a number of robots actually used in industrial worlds has been restricted in appropriately supervised factories. However, it has been anticipated to realize the robots that can work in various situations, for example, searching survivors in a disaster site, explorations on uncharted planet and so forth.

One of the promising solutions is to develop a walking robot. Due to this, many walking robots has been developed and demonstrated in the literatures [1], [2]. However, in general, conventional walking robots had less mobility, since their body structures have high stiffness.

Meanwhile, insects, especially a cockroach, can accomplish fast locomotion even if in rough terrain, thanks to the flexible body compliance mechanisms derived from their musculoskeletal attributes.

According to this, in the present study, we developed a hexapod walking robot by focusing on the structural compliance mechanisms. The compliance mechanism of the developed robot was implemented by the combinational use of a DC servomotor and a linear DC solenoid. Through preliminary experiments, the validity of the leg compliance mechanism is demonstrated.

2. Related Researches

In order to design a better walking mechanism, many researchers have referred to the walking mechanisms of living creatures. Especially, a cockroach has often been focused on, since the walking speed is the fastest in insects. For instance in [3], cockroach locomotion on the treadmill was captured by high-speed camera to analyze the joint movements.

As shown in **Fig.1**, the leg of a cockroach consists of three segments, i.e., Coxa, Femur and Tibia. Here it should be noted that both joints between Coxa-Femur and Femur-Tibia are connected by soft tissue. This implies that each joint works much like that of a ball and socket joint, and it can contribute to the leg compliance for the purpose of shock absorbing. In recent robotics, some researchers have developed bio-mimetic walking robots focusing on the leg compliance. Clark et al. [4] have developed a hexapod robot “Sprawlita”. They also focused on cockroach‘s rapid locomotion realized by the structural compliance of muscles and an external skeleton. Thus, the robot could absorb a shock from the ground surface by using flexible legs made of air actuators. The gait pattern of the robot was fixed on tripod gait (see **Fig.2**), namely unadjacent three legs are simultaneously swung. This walking pattern is popular in real insect world, and they can walk quickly by the pattern.

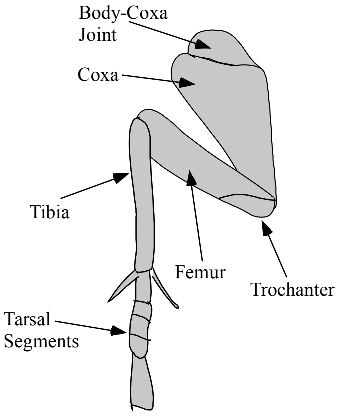

Fig.1 Cockroach front leg

On the other hand, Komsuoglu [5] et al. has developed a hexapod robot “Rhex.” The robot has six legs that can rotate 360 degrees just like as wheels using DC motors. Each leg of the robot was formed by arc shape bent rod that makes compliance. Although it should be carefully discussed whether this kind of robots can be classified as walking robots, the robot can move quickly in rough terrain.

However, most of conventionally developed walking robots excluding the above examples have the mobility problem, because their joints are directly attached to DC motors. This results in increasing the structural complexities and weight of the robots.

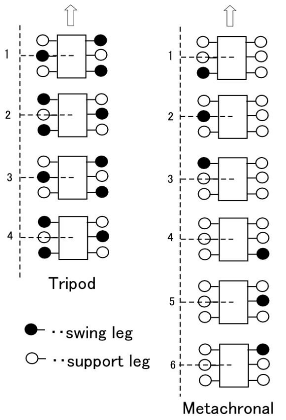

Fig.2 Insect gait pattern: Tripod and Metachronal

According to this, we have developed a hexapod walking robot by focusing on the structural compliance mechanism of cockroach. The compliance mechanism of the developed robot is implemented by the combinational use of a DC servomotor and a linear DC solenoid. Here, the motor is used for rotating each leg forward/backward, and the linear solenoid is for producing an impulsive force. The magnetic force of the solenoid also gives a passive compliance against disturbance forces.

In addition, the joint between the motor and the solenoid is connected by organic material (acrylic) rods to mimic the flexible leg of cockroach. This exactly contributes to make compliance as opposed to the external force.

3. Robot Hardware

Fig. 3 and 4 shows the CAD design and Photograph of hexapod robot. Six DC motors and six linear DC solenoids are used as actuators. The linear magnetic solenoid is stretched 10mm by sending the electric current. The robot consists of two-deck frames made by aluminum. The robot length is 180mm, the width is 247mm and the height is 85mm. The extensive width increases the stability against the lateral direction force. The total weight is about 1.0kg (in the case of external electric power supply). At the present time, no sensor is attached to take in the external information from the environment.

Fig. 5 shows the control block diagram. The CPU (H8/3048F; Hitachi Co., Ltd,) controls twelve actuators (six DC motors and six linear DC solenoids). DC motors are actuated by PWM control from CPU. The clock frequency is 16MHz. The motor torque is $8.4kg \cdot cm$ and the rotation speed is $0.08s/60°$. The power voltage is $6.0V$. And the receiver of radio control system for the remote manipulation is attached.

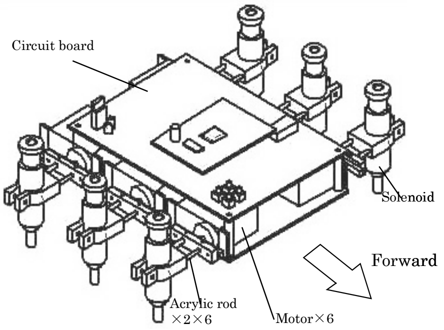

Fig.3 Design structure of hexapod robot

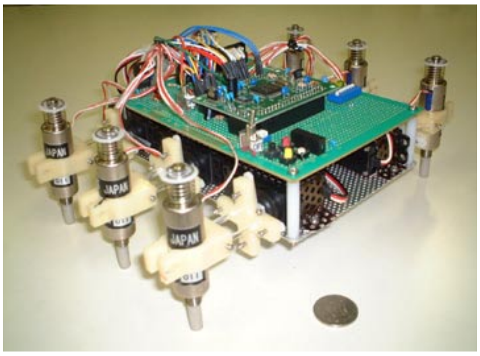

Fig.4 Photograph of hexapod robot

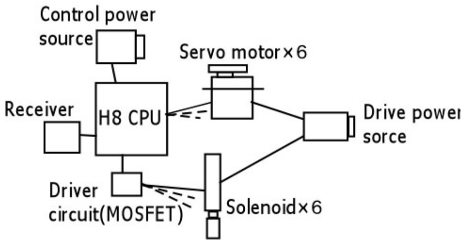

Fig.5 Control block diagram

4. Leg Structure

4.1 Leg compliance

The Photograph in **Fig.6** shows a leg structure. Many of insects utilize the flexibility of muscle and skeleton systems as a shock absorber during locomotion. In the present research, passive compliance mechanisms are also embedded in the leg structure. As shown in **Fig.7**, a pair of acrylic rods is installed at the root of leg, which can be bent flexibly about the motor axis.

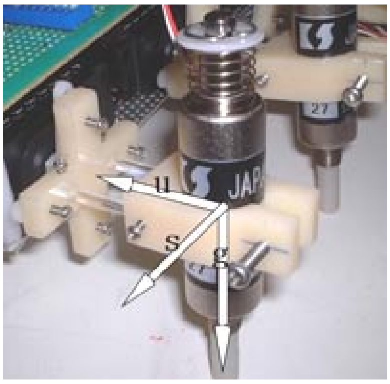

Fig.6 Leg structure

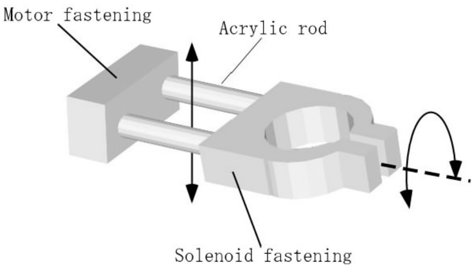

Fig.7 Bending of Acrylic rods

When the force F is added to the edge of acrylic rod, the bending width r and angle θ are given by the following equations.

$$r = \frac{FL^3}{3EI_z} \tag{1}$$

$$\theta = \frac{FL^2}{2EI_z} \tag{2}$$

where, L is rod length, E is Young's modules, $I_z = \pi d^4/64$ is geometric moment of inertia (d is diameter). The bending force by the weight of acrylic rod is ignored because it is very lighter than the body. Supposing F=5N is applied, from (1) and (2), the bending width r is 2.8mm, and the bending angle θ is 8.25 degrees, where the design parameters are L =0.03 m and

$$E = 3.92\times10^9\ N/m^2$$

These values coincide with the measured ones.

In addition, linear DC solenoid is used to absorb another external disturbance orthogonal to the motor axis.

4.2 Solenoid repulsion force

The solenoid generates the repulsion force to support the body. In the tripod gait, each three legs are moved alternately. Since the total weight of robot is about 1.0kg, the repulsion force of each leg is required to be more than 400g. **Fig.8** shows the relation between the repulsion force and the supplied electric power. It is seen that the repulsion force is in proportion to the supplied power. So the solenoid is driven by about 10 w. The solenoid takes 25 msec to be lengthened by 10mm. On the other hand, the shortening of solenoid is driven by the spring, which takes 34 msec to return to the original position.

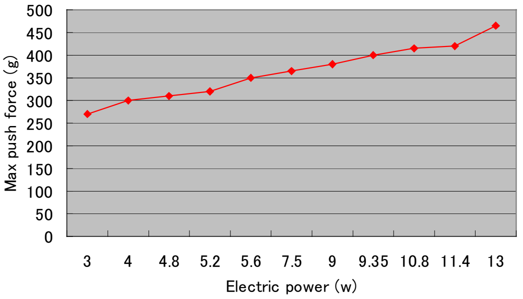

Fig.8 Solenoid repulsion force and supplied power

4.3 Leg rotation and extension/contraction

The leg is also driven to propel the body forward and backward by the DC servomotor with PWM control. The rotation angle of each leg is set up with ± 30 degrees (forward(+) and backward(-)).

Fig.9 shows the driving time charts of the motor and solenoid in each leg. The upper graph shows the motor rotation angle, where +30° means that the leg is at the forward position, – 30° at the backward position.

The lower shows the extension and contraction timing chart of the solenoid. The solenoid is lengthened to +10mm at the maximum.

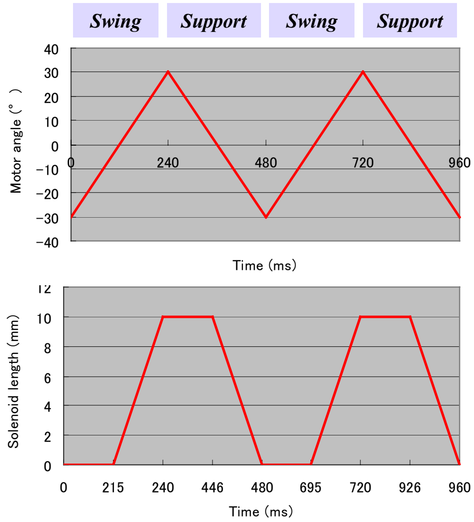

Fig.9 Drive timing of the motor and solenoid

As seen from the figure, the leg has been lengthened to 10 mm just when reaching the maximum forward position. Then, it has been shortened just when reaching the backward position. Therefore, when the leg is rotated from +30 to -30 degrees, it is at the support phase. Inversely, when it is rotated from -30 to +30 degrees, it is at the swing phase. One cycle of gait is 480 msec in the present case.

5. Locomotion Control

5.1 Direction control

It is necessary to turn right and left in addition to going straight, in order for a robot to move free. The present hexapod robot can turn by making the step of legs on either side asymmetrical. When turning rightward, the step of three legs in right side is made smaller than the left side step. When turning leftward, it is in reverse.

We investigated in the experiment how the turning radius of robot could be adjusted by changing the rotation angle of one-sided legs. The rotation angle of the other side leg is fixed between ±30 degrees. As shown at **Table.1**, the turning radius can be controlled between 11 cm and 60 cm. When the rotation angle of one-sided legs is fixed at 0 degree, the turning radius is 11 cm. Then, the robot turns by setting the middle leg as the central axis.

Table1 Turning radius of robot

Rotation angle of one-sided legs	Turning radius (cm)
0	11
5	25
10	34
15	60

5.2 Velocity control

It is possible to control the forward and backward velocity of robot by shifting the drive timing of the linear solenoid as shown in **Fig.10**. The solenoid is extended when the rotation angle of the motor reached backward to +15°(mode 1), +10°(mode 2), +5°(mode 3) and +0°(mode 4).

As shown in **Fig.11**, the robot is moved from forward to backward as the drive timing of solenoid is shifted to the right. The robot does not move at mode 2, where the solenoid is extended ranging from the backward and forward rotation of leg. This means that the leg is at the support phase during the corresponding span. Therefore, the forward and backward forces actuate the leg alternatively. As a result, the robot remains stepping. At mode 3 and 4, the robot moves backward. Especially, the phase at mode 4 is completely reversed comparing with Fig.9.

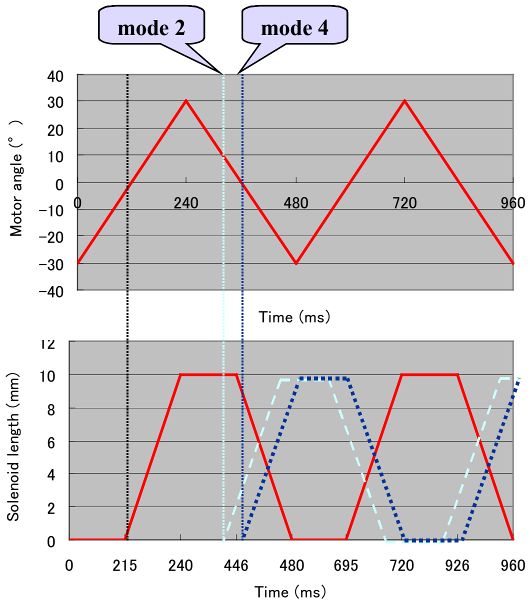

Fig.10 Velocity control by shifting the solenoid drive timing

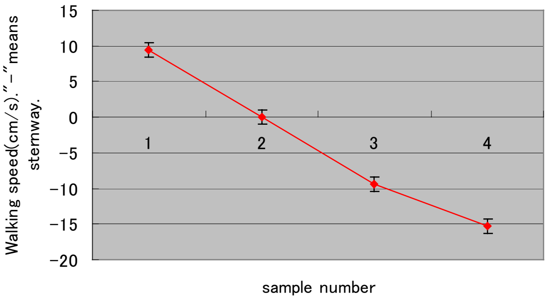

Fig.11 Relation between solenoid drive timing and robot velocity

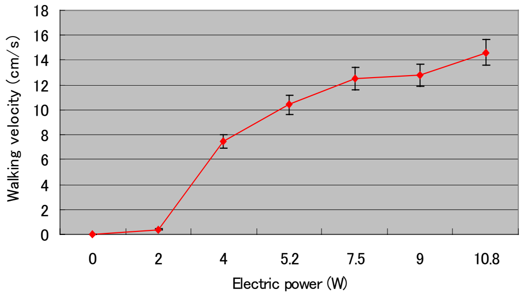

Fig.12 Relation between robot velocity and electric power

The velocity of robot also depends on the electric power supplied to the solenoid. **Fig.12** shows the relation between the velocity and electric power of solenoid at the tripod gait pattern on the hard plastic desk. Then, the rotation speed of motor is fixed. The fastest velocity is 14.6cm/sec at the electric power 10.8w. The robot cannot walk under around 2W. It is too small power to lift up the body. It is known that the repulsion force of solenoid is effective for the walk.

5.3 Radio control

The FM wave radio control system is attached in order to steer the robot on real time. The transmitter has four channels. The receiver carried on the robot is very light, the weight of which is 8g. The signal sent from the transmitter is changed into the pulse signal of TTL level at the receiver, and the pulse signal is directly sent to H8 microcomputer.

Fig.13 shows the picture sequence in the tripod gait. It is seen that the extension and contraction of solenoid is performed corresponding to each leg rotation. The picture sequence in **Fig.14** shows the robot locomotion controlled by the radio control system. It is possible to avoid the obstacles easily by manipulating the transmitter.

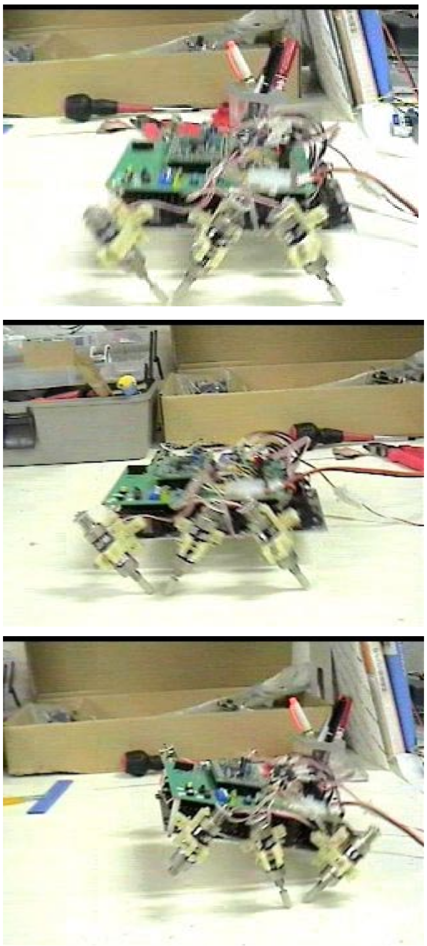

Fig.13 Tripod gait

6. Energy Consumption

At the present time, the robot gets the electricity for the motor and solenoid from the external source. However, in the future, it is required to carry on the battery system in order to move around autonomously at the outdoors. So it is necessary to estimate the electric power consumed by the actuators beforehand. The power consumption during one cycle of gait was measured. The results are as follows.

1) Motor power consumption

$$6V \times 0.3A \times 6 = 10.8W$$

Six motors are always derived. Therefore, total $10.8W$ is required.

2) Solenoid power consumption

$$18V \times 0.6A \times 3 = 32.4W$$

Three solenoids are derived at once at the tripod gait. The total is $32.4W$.

3) Electronic circuit power consumption

$$15V \times 0.08A = 1.2W$$

The total power consumption is 44.4W.

7. Conclusion

We designed and developed the hexapod robot that had flexibility at legs. And it was shown that the simple program could make a high-speed walk. It was verified that a pair of acrylic rods and the linear solenoid contributed to the leg compliance effectively. The maximum extension of present solenoid was 10mm, which shows that there is only 10mm clearance between the foot tip and the ground. It will be not sufficient to clear an obstacle. It is required to develop the solenoid with longer extension. In addition, it is better to install some sensors, for example, touch sensor on the leg and gyroscope on the body.

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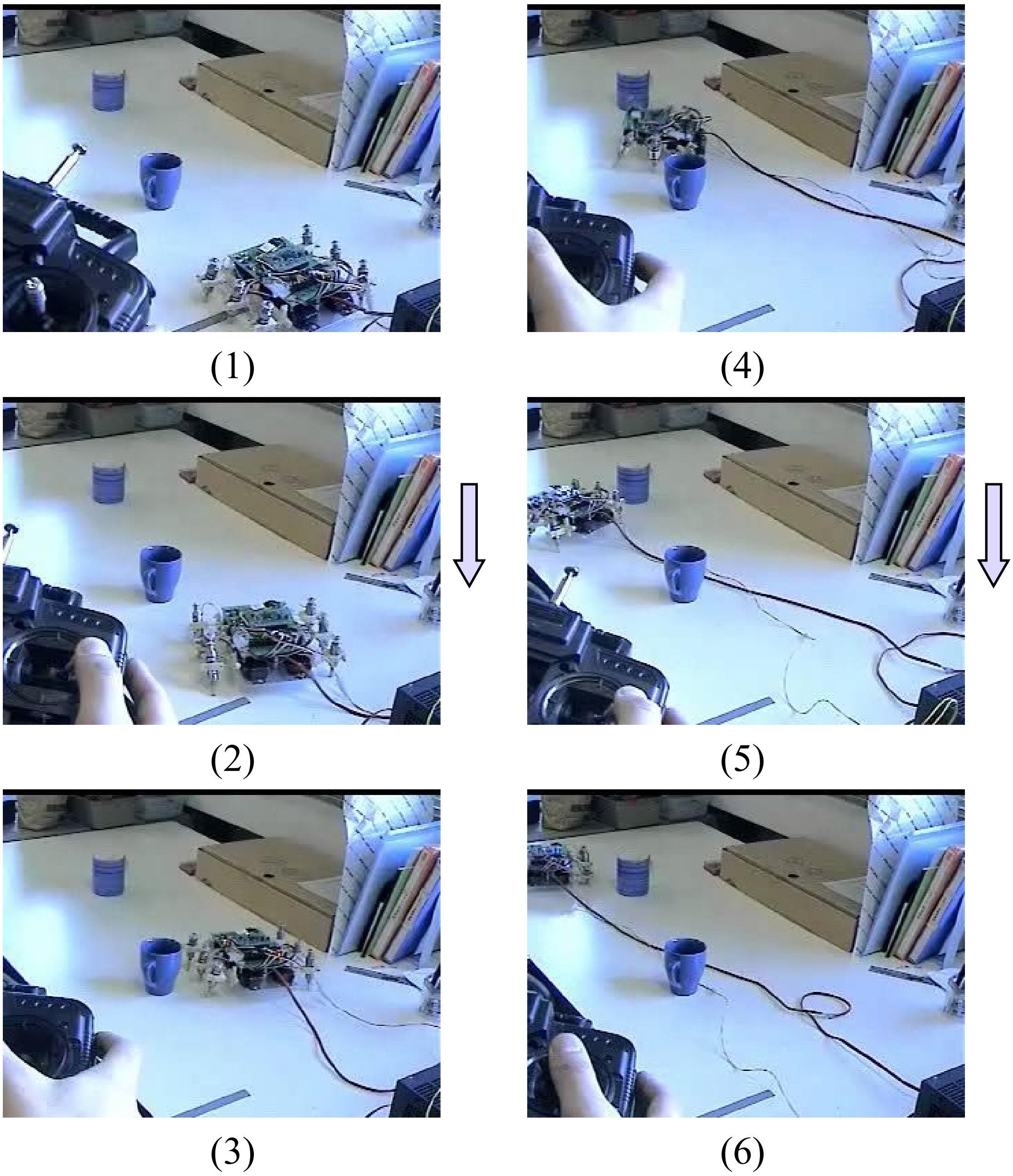

(1) (4) (2) (5) (3) (6)

Fig.14 Robot locomotion by the radio control system

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