Design and prototype of a six-legged walking insect robot

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Abstract
Purpose – This paper seeks to develop a novel legged robot.
Design/methodology/approach – First, the paper models the legged robot using 3D computer model by intelligent inspiration of biological principles. Then, based on this model, it develops the prototype of the legged robot.
Findings – A novel motion mechanism is used and only two actuators are used for driving the system.
Originality/value – The modelled legged robot is original in terms of the developed motion mechanism.

Keywords Prototypes, Motion, Actuators, Robotics

Paper type Research paper

1. Introduction
In recent years, numerous studies on legged robots have been reported (Delcomyn and Nelson, 2000; Huang and Nonami, 2003; Ohnishi, 2004a, b; Quinn et al., 2001; Siegwart and Nourbakhsh, 2004). Scientists and engineers have taken an interest in constructing legged robots with biologically-based designs (Quinn et al., 2001). The main advantage of legged robots is their ability to access places impossible for wheeled robots.

By copying to the physical structure of legged animals, it may be possible to improve the performance of mobile robots. To provide more stable and faster walking, scientists and engineers can implement the relevant biological concepts in their design.

The most forceful motivation for studying legged robots is to give access to places that are inaccessible or too dangerous for human beings. Legged robots can be used for rescue work after earthquakes and in hazardous places such as the inside of a nuclear reactor, giving biologically inspired autonomous legged robots great potential.

Low power consumption and weight are further advantages of walking robots, so it is important to use the minimum number of actuators. Tokgöz and Yapilican advised by Alli designed a six-legged robot called Robomali T5 using only two actuators (Tokgöz and Yapilican, 2004). Motivated and informed by this study, we have developed the motion of their robot and added springs to the prototype to give more flexibility to the legs and mimic muscles.

2. Design of six-legged walking insect robot
In this study, we design a six-legged walking insect robot whose structure is based on the biomechanics of the cockroach (Figure 1). The walking robot is driven by two stepper motors. A six-bar Watt’s chain forms the kinematic chain for the legs, and is actuated by a cam mechanism and transmission bar. Springs mounted on the legs mimic important muscle characteristics. The motion mechanisms are governed by a PLC controller.

This paper consists of six sections. Section 2 discusses the design steps of the six-legged walking insect robot. The gait of the walking robot is given in Section 3. The prototype is investigated in Section 4, and Section 5 describes the control part of the walking robot. Section 6 presents the experimental work. Finally, Section 7 presents some conclusions and future work.
2.1 Design of the leg mechanism

For legged robots, 2 DOF is the minimum required to move a leg forward by lifting and swinging.

Figure 2 shows the leg mechanism, using a Watt-chain six-bar mechanism to imitate the cockroach (insect) leg. We chose a six-bar mechanism because of its superior force-transmission angle and bigger oscillating angle in comparison with other types such as the four-bar mechanism (Norton, 2004). Force transmission is very important for leg mechanisms, because of the point contact with the ground. The leg mechanism itself has one DOF for lifting, whilst the base of mechanism has another DOF for swinging. The leg mechanism, with its body size shown in Figure 1, is modelled with Solid Works. It has six links and seven cylindrical joints. The body size and link dimensions are determined from the maximum swing and lift angles. Each link is created by entering its shape and reference coordinates. To mate the contact surfaces of the parts, the assembly bar of the assembly-mating menu is used. Then the component is rotated around an axis, specifying the desired axis and rotation for the selected surfaces.

To generate more stable walking on rough ground and mimic muscles, the springs are mounted between link1 and link2 and between link2 and link3.

2.2 Design of the cam-shaft and transmission bar

The main differences between this study and other hexapod robot studies are the number of actuators and the motion mechanism used in the leg motions. The related literature (Table V, Huang and Nonami, 2003; Lin et al., 2006, 2005; Luk et al., 2005) indicates that at least one actuator is used for the step motion of each leg. This necessitates a minimum of six actuators for a hexapod robot. However, in this design, the up/down motions of tripod legs are obtained by rotating both the left and right cam-shafts in the same direction using just one actuator, rather than using different actuators for each leg (Figures 3 and 4). The single actuator performs all tasks necessary for the up/down motion and simplifies the control of the system. Figure 3 shows the cam-shaft used for transmitting the leg-lifting motion. The cam-shaft, one of the most important parts of our design, is also modelled with...
Solid Works. The developed cam-shaft is used for lifting three of legs and grounding the others during the walking, and enables tripod gait using only one stepper motor. At the same time, it simplifies the control problems.

Two cam-shafts actuated by the same stepper motor have been used for the left and right side legs. As seen in Figure 4, these cam-shafts rotate simultaneously.

Figure 5 shows the transmission bar and connecting rod used for the swinging motion of the legs. This simultaneous left-and-right-side-walking mechanism is driven by one stepper motor. In addition, each leg of the insect robot is mounted on the fixed bar. The right tripod and left tripod legs, oscillating along the x-axis, pace forward by virtue of the forward/backward motion of the transmission bar. This motion is produced by just one actuator driving the connecting rod. The lifting legs go forward one step driven by the connecting rod and transmission bar when the stepper motor rotates one revolution. The legs are connected to the fixed bar while the leg joints are connected to the transmission bar by the connecting links shown in Figure 4. The legs swing \( \pm 15^\circ \) and the transmission bar translates 0.02 m when the connecting rod moves through one cycle.

Figures 6, 7(a) and (b) show positions of the transmission bar and the connecting rod in the top view of the legged robot.

2.3 Assembly of the six-legged insect robot
The created parts previously saved in the assembly file were assembled using the assembly mating function in Solid Works. After defining the contact surfaces, the legged robot is modelled using move and rotate functions. The result is shown in Figure 8. Finally, 3D animation of the modelled legged robot was developed in COSMOSMotion.

3. Gait of the walking robot
Since, the legged walking robots have been biologically inspired, it is meaningful to examine biologically successful legged systems. Most insects use a characteristic and stereotypical gait (sequence of leg movements) when
they walk. In this alternating triangle gait, the front and rear legs on the one side of the body and the middle leg on the other side move more or less together, and alternate in their movements with the triangle of the remaining three legs. This, which is also called the tripod gait, is the fastest of the wave gaits and is commonly observed in insects walking on smooth surfaces. One can observe the gait pattern by video clip recording.

The gait of our legged robot is explained in this section. The left- and right-side legs are sequentially numbered L1, L2, L3 and R1, R2, R3, as shown in Table I, Figures 8 and 9. Once the legs L1, L3 and R2 have begun their motion, R1, R3 and L2 become support legs. In the second step, while R1, R3 and L2 are in the motion, L1, L3 and R2 become support legs. Table I also presents these situations, where the legs supporting the body are represented by \( v \) and those floating are represented by \( Y \). The walking directions of the legs are shown in Figure 10. The maximum stride of each leg is 0.098 m and the walking cycle is 1.82 s. The maximum lift of each leg is 0.035 m. The maximum angle of the legs when
The speed of the legged robot is constant during walking (5.40 cm/s).

**4. Prototype of the six-legged walking insect robot**

After full verification by realistic 3D animation of the CAD model using the COSMOSMotion program, a physical prototype was constructed based on the CAD model to save time and reduce equipment damage and faults.

Figure 11(a) and (b) show the overview of the prototype legged robot. It has a 24V battery power supply, a Siemens SIMATIC PLC device as controller, and three mechanical switches as sensors. Table II indicates the equipment and devices installed on the board of the legged robot.

Figure 12 shows the PLC block diagram and the power supply mounted on the legged robot. The legged robot uses two 6V stepper motors with their power and control systems on board. One stepper motor drives the left and right-side cam-shafts while the other drives the left and right-side connecting rods and transmission-bar groups.

**5. PLC control of the walking robot**

Three mechanical switches are used as input sensors for the six-legged walking robot. The robot legs are driven by two stepper motors from the signals from the mechanical switches. The control of the legged robot is realized using an S7-200 Siemens Micro PLC set. The ladder diagram, shown in
Figure 13 has been prepared for the tripod gait of the legged robot, then downloaded to the PLC from the PC. This program controls the stepper motors by means of the mechanical switch signals. Table III indicates the inputs and outputs installed on the ladder diagram.

The left and right tripod legs go forward one step (0.098 m), respectively, each time the mechanical switch with PLC address I0.2 rotates $180^\circ$; then the first stepper motor, with address Q0.0, is driven. When going forward one step, the mechanical switches labelled I0.3 and I0.4, driven by the transmission rods, respectively, send signals to drive the second stepper motor at Q0.2. The cam-shaft rotates one revolution when the second stepper motor is driven, operating the up/down motion of the tripod legs. Thus, the walking action is produced by the ladder diagram. The output with address C23 is a digital counter to determine the step number.
Figure 10 The leg directions during walking

Figure 11 (a) The front view of the prototype; (b) the top view of the prototype
6. Experimental results

In this experimental study, numerous jogging runs have been performed by the insect robot shown in Figure 11 with dimensions $30 \times 25 \times 19$ cm. Potentiometers measured the angular displacement of each leg in both $x$- and $y$-axes. In addition, an analog/digital converter (NEMA4X-SCADA) and digital oscilloscope (FLUKE43B) gathered angular displacement data. These data are presented in graphical form.

The lower-half of Figure 14 shows the typical sequence of leg contact conditions. It shows a top view and a side view. In the first interval, the tripod legs start to lift off. They remain raised and then touch down. Finally, there is the interval of the fixed tripod stance for the next step. The upper-half of the figure indicates the relationship between these four phases of leg positions, from data gathered by the potentiometers on the legs.

Table IV indicates the average times of the four phases and the total time of the complete stride, measured at 1 kHz and averaged over 25 experimental runs. This table has been obtained from Figure 14 (Saranli et al., 2001).

7. Conclusion and future work

Intelligent biological inspiration has been used to design a simple and more insect-like robot for the better application of current technology. Simple engineering solutions have been used, rather than directly copying the insect moving mechanism. The legged robot developed in this study loosely imitates the cockroach leg mechanism. Only two stepper motors are needed to achieve the tripod gait. Reducing the number of drive motors leads to a lighter structure and simpler control. It is well-known that the complexity of a control system depends on number of actuators used, and more actuators mean more difficult control and higher cost. These problems can be overcome by designing special mechanisms. The cam mechanisms and connecting rods and springs in our design reduce the number of actuators and ease the control and cost of the insect robot. Table V summarises this and compares our robot with others in the literature, and indicates that the speed of our robot compares favourably.

To reduce equipment damage and faults and save trial-error time, the design was modelled on Solid Works and the animation was realized on COSMOSMotion. A prototype six-legged walking insect-like robot was built with control from a PLC.
In this study, only straight-line trajectories were realized. We continue our studies to implement more general trajectories and climbing. We will try to use only one actuator to drive the cam-shafts and connecting-rods by mounted additional cam mechanisms. The addition of another actuator will increase the mobility of the legged robot.

Intelligent biologically inspired walking robots have great potential in inaccessible places and those dangerous to humans and currently available equipment. In the future, further research on biologically inspired robots will improve the performance of the designed walking robots.
**Figure 14** The four intervals during the $i$th tripod stride $S(i)$

<table>
<thead>
<tr>
<th>Phases</th>
<th>Average time (s)</th>
<th>Percentage of time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tripod stance (touchdown transient to wait)</td>
<td>0.82</td>
<td>45.05</td>
</tr>
<tr>
<td>Liftoff Transient</td>
<td>0.18</td>
<td>9.89</td>
</tr>
<tr>
<td>Tripod stance forward</td>
<td>0.64</td>
<td>35.16</td>
</tr>
<tr>
<td>Touchdown transient</td>
<td>0.18</td>
<td>9.89</td>
</tr>
<tr>
<td>Total</td>
<td>1.82</td>
<td>100.0</td>
</tr>
</tbody>
</table>

**Table IV** Experimental phase relations in insect robot tripod gait

**Table V** Actuator number, leg number and speed of some leg robots

<table>
<thead>
<tr>
<th>Robots</th>
<th>Number of actuators</th>
<th>Number of Legs</th>
<th>Speed (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our insect robot</td>
<td>2</td>
<td>6</td>
<td>5.40</td>
</tr>
<tr>
<td>Rhex</td>
<td>6</td>
<td>6</td>
<td>--</td>
</tr>
<tr>
<td>Robug III</td>
<td>16</td>
<td>8</td>
<td>10.0</td>
</tr>
<tr>
<td>Dante II</td>
<td>6</td>
<td>6</td>
<td>1.70</td>
</tr>
<tr>
<td>Genghis</td>
<td>6</td>
<td>6</td>
<td>3.80</td>
</tr>
<tr>
<td>Commet</td>
<td>6</td>
<td>6</td>
<td>5.00</td>
</tr>
</tbody>
</table>

Sources: Angle (1989), Bares and Wettergreen (1999), Barfoot et al. (2006), Huang and Nonami (2003), Lin et al. (2005, 2006) and Luk et al. (2005)
References


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