Motion mechanism concept and morphology of a single actuator tetrapod walking spider robot: the ROBOTURK SA-2 Robot

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Abstract

Purpose – This study seeks to develop a novel eight-legged robot. Additionally, this study defines design and control of an eight-legged single actuator walking ROBOTURK SA-2 spider robot based on the features of a creatural spider.

Design/methodology/approach – First, the single actuator eight-legged tetrapod walking spider robot was modeled on solid works and then the animation of the model was realized to ensure the accurate walking patterns and more stable walking. Based on this model, the novel prototype of the single actuator eight-legged walking spider robot was constructed.

Findings – A novel motion mechanism uses only one actuator for driving the system.

Originality/value – The modeled single actuator eight-legged robot is original in terms of the developed motion mechanism.

Keywords Robotics, Motion, Actuators

Paper type Research paper

Introduction

In last years, a lot of studies on legged robots have been published (Pretto et al., 2008; Soyguder and Alli, 2007; Delcomyn and Nelson, 2000; Huang and Nonami, 2003; Ohnishi and Asakura, 2004a, b; Siegwart and Nourbaksh, 2004; Saranli et al., 2001; Yang et al., 2009; Hirukawa et al., 2005). People have considered in manufacturing legged robots whose designs are based at least in part of biological principles (Ho and Lee, 2009; Anshar and Williams, 2007; Ho et al., 2007; Luk et al., 2005; Norton, 2004; Angle, 1989). The basic advantage of legged robots is to be capable of going where wheeled robots are not capable of. That is why, scientists and engineers may be able to improve the performance of mobile robots by copying to the physical structure of legged animals. Because of more stable and fast walking, one can implement the relevant biological concepts in their design. Further, the motivation of the above studies on legged robots is to have potential for use in places which are too dangerous for humans. They are capable of being used for rescue works after earthquakes and in hazardous places such as the inside of a nuclear reactor.

RHEX is one of the most known six-legged robots as the example of legged robots (Saranli et al., 2001). It has multi-functional mobility and high performance. In addition to that, Lauron II designed by Forschungszentrum Informatik (Berns et al., 1993) and Genghis designed by Massachusetts Institute of Technology are the examples of six-legged robots (Angle, 1989). The control of Genghis has been performed by six actuators while Lauron II has been controlled by 12 actuators. Robug-III, eight-legged spider robot, is also one of the most popular robots (Luk et al., 2005). It has been actuated by 16 DC motors, each pair is located to its each leg. However, mobile robots must consume minimum energy and work as high performance because they carry their power sources themselves. That is why, this aim can only be realized by usage of the minimum number of actuators and design of suitable mechanisms. Formerly, Soyguder and Alli (2007) designed six-legged robot using only two actuators. In this study, ROBOTURK SA-2 with eight legged and only one actuator has been designed for the aim of defense industry, natural disasters, etc. (Figure 1(a) and (b)). This robot has features of low energy consumption, minimum weight and easy control by decreasing the number of the used actuators. The most important feature of the designed robot is to realize straight walking like spiders in nature using only one DC motor (with planetary gear; 28:1) actuating all legs and joints of the robot. However, the other types of gaits have not been considered in this study.

The kinematics chain of the legs actuated by the CAM mechanism and transmission bar is six-bar Watt’s chain. The springs are mounted to the legs to mimic important muscle characteristics. Programmable logic controller (PLC) is used for controlling the motion mechanisms.

This article has six sections. The next section presents the steps of motion mechanism concept and morphology of a single actuator walking spider robot. Moreover, the prototype model and innovations are investigated in this section. Workspace and walking plan of the ROBOTURK SA-2 spider robot is given in third section and fourth section describes physical design of the single actuator eight-legged walking robot. Fifth section includes the control part of the walking robot. The following section presents the experimental works. Finally, the last section includes some conclusion remarks and future works.
Motion mechanism concept, morphology and innovations

In all robotics applications, mechanical complexity is one of the major sources of failure and considerably increases the cost (Saranli et al., 2001). Therefore, our design emphasizes mechanical simplicity and easy control. In addition to that, it is intelligent inspiration rather than trying to copy animals, that is not always possible for the current technology. In this study, a different morphology, superior to those of the current legged robots, has been used for the designed robot. The used motion mechanism couples the robot joints for the aim of reducing the number of actuators and simplifying the control problem. Furthermore, actuators are generally heavy and reducing the number of actuators is also able to save energy consumption. Autonomy, a critical component of our aspiration toward real-world tasks in unstructured environments outside the laboratory, imposes very strict design constraints on the hardware and software components. It is often impossible to achieve with simple modifications to a system otherwise designed for non-autonomous operation. These constraints also justify our preference for overall simplicity, in particular the minimum amount of actuation and energy.

The mobility of the legged robot is 1 degree of freedom (DOF) and all legs are identical. The main target for the legged robot in this study is to walk on smooth ground and verify the tetrapod gait pattern similar to that observed in the spider. For more information, Figure 2 shows body size of the single actuator eight-legged walking spider robot.

In this study, the designed eight-legged walking robot with a single actuator is called ROBOTURK SA-2, owning many innovations (Figure 1(a) and (b)). The innovations of ROBOTURK SA-2 as follows:

- the number of actuators;
- the CAM mechanism mounted in the back of the eight-legged spider robot;
- mounting springs to much or less mimic muscles; and
- the characteristics of gait are similar to those in nature.

Design of motion mechanism

The actuator of the robot

The main aim of this study is to realize the straight tetrapod gait using minimum number of actuators. The proposed design has some drawbacks such as performing one type of gait and limitations on the mobility of the robots. These limitations can be achieved by using one more actuator. The authors are planning to include these ideas for the future studies. The main feature of the spider robot owning the straight tetrapod gait like spiders in nature by using only single DC motor is to be 1 DOF. The motions of the all legs and joints are provided by Geneva, CAM mechanisms and springs driven by single DC motor. Providing to contact with the ground for the marked legs and lifting up/down motions of the other legs have been realized by means of CAM and Geneva mechanisms driven by same DC motor. It is seen in Figures 3 and 4 that each of the links mounted on the CAM mechanisms provides the legs to contact with the ground. Furthermore, the Geneva mechanism rotates only 120° and then waits 240° while the DC motor rotates one revolution. Hence, the motion of the Geneva mechanism transmits to the CAM mechanism so that the legs simultaneously contact with the ground. At the same time, the same DC motor in each revolution performs the walking of the spider robot by the belt-pulley mechanism making the legs leaving from the ground translate forward by the means of the transmission bar and connecting rod.

The obtained results of the minimizing of the number of actuators as follows:

- The energy consumption has been minimized by decreasing the number of actuators (the designed spider robot uses single DC motor for only the straight gait in this study while the similar robots in the literature use at least six or eight DC motors (Soyguder and Alli, 2007; Huang and Nonami, 2003; Saranli et al., 2001; Luk et al., 2005; Angle, 1989; Berns et al., 1993).
- Decreasing the number of actuators makes the control easy.
- The structure of the robot can be easily formed.
- The cost has been minimized.
- The drawbacks are realizing one type of gait and limitations on the mobility of the robot.

Function of the transmission bar and connecting rod

The transmission bar and the connecting rod are used for swinging motion of the legs, as shown in Figure 5. The left and right side of transmission bar and connecting rod group
of the spider robot are simultaneously actuated by the same DC motor. Furthermore, each leg of the spider robot is placed on the fixed bar. The right tetrapod and left tetrapod legs, oscillating through the rotating axis, pace forward by the forward/backward motion of the transmission bar. This motion is realized by only one DC motor which drives the connecting rod (Figures 3 and 4(a) and (b)). That is, the lifting legs go forward one step by means of the connecting rod and transmission bar when the DC motor rotates one revolution. It is seen in Figure 6 that the legs are connected to the fixed bar while the leg joints are connected to the transmission bar by means of the connecting links. The swing angle ($\theta$) limits $\pm 15^\circ$ while the transmission bar translates 0.02 m when the connecting rod moves one period, as in the previous study of the authors (Soyguder and Alli, 2007). The positions of the transmission bar and the connecting rod in the top view of the legged robot are shown in Figure 7.

**CAM mechanism mounted to back of the spider robot**

The CAM mechanism provides that the legs forming the gait of the robot contact with the ground as shown in Figure 8. In the each step of the gait, the CAM mechanism makes the some legs contact with the ground while the some legs stop contacting with the ground depending upon the character of the gait. The innovations because of using the CAM mechanism are followings:

- it is no need to use different actuators for each leg because the CAM mechanism realizes to contact the each leg with the ground for the straight gait; and
- the period of service needs and technical defaults decreases because of using the CAM mechanism instead of using many number of DC motors.

**Springs**

The springs transmit the motion obtained by the CAM mechanism to the joints (Figure 9). The existence of the CAM mechanism and springs cause the easy control of the spider robot and minimizing the number of actuators used. The innovations because of using the springs are followings:

- using the springs in the leg joints makes the legs gain part of the features of muscles like those in nature; and
- the motion is transmitted to the joints by the extension and compression of the springs partly like the flexion and laxation of muscles in living being.
**Figure 4** (a) and (b) Geneva mechanism and connecting rod

(a) Genova mechanism

(b) Transmission-bar and Connecting-rod

**Figure 5** The transmission bar and connecting rod group

**Figure 6** The working principle of the CAM-shaft
Solid model of the single actuator eight-legged spider robot

The formed parts saved in the assembly file before, were assembled by using assembly mating function in solid works. The legged robot was modeled using move and rotate functions after the contact surfaces had been selected. The modeled legged robot is shown in Figure 10(a) and (b). Consequently, 3D animation of the modeled legged robot has been developed in COSMOSMotion.

Workspace and walking plan of the ROBOTURK SA-2

The walking stability of the eight-legged robot is provided by the four legs becoming support legs in each walking step (Ritzmann et al., 2004). Since a creatural spider walks in a style of four-legged support (R1 the first and R3 the third leg of the right side and L2 the second and L4 the forth leg of the left side) and the others move forward. It is also seen in Figure 11 that L1 and L3 on the left side and R2 and R4 on the right side become support legs in the first step while L2 and L4 on the left side and R1 and R3 on the right side become support legs in the second step. These situations are also presented in Table I that the leg supporting the body are represented by ● and the ones floating are represented by ○.

The straight walking is realized by repeating this cycle. The most important feature in this design is that the legs are connected to the clippers on the fixed bar as shown in Figure 5. The leg clippers are connected to the transmission bar by means of a connecting rod. Further, the transmission bar is driven by the connecting rod. Transmission bar translates forward 0.02 m from the reference point in one cycle of the motion of the connecting rod. Then, this motion provides the translation of the spider robot by means of the $\pm 15^\circ$ ($\theta$) angular displacement of the legs depending on walking patterns. Besides, the up/down motion of the legs is realized by the CAM mechanism. By the way, the motion of the CAM mechanism is provided by 120° angular displacement of Geneva mechanism transmitting to the CAM-shaft by the bevel gears. After that, the support legs stop touching with ground as they rotate between $0^\circ$ and $+60^\circ$ ($\varphi$) from the ground to the up position whereas the other legs touch with the ground by moving from up to down as shown in Figure 6. Furthermore, Figures 12(a) and (b) and 13 show the trajectory of each leg in the workspace of the spider robot. In addition, each leg is connected to the different points of the connecting rod therefore each connecting rod has different length as shown in Figure 5. These connections provide the designed robot to mimic the real spider walk patterns in nature. The rotation directions of the legs in each step are shown with the arrows in Figure 5.

From the animation of the CAD, the walking directions of the legged model are shown in Figure 14, where the maximum stride of each leg is 0.098 m and the walking cycle is 1.82 sn. Further, the maximum lift-up height of each leg is 0.035 m, the maximum angle ($\varphi$) of the legs corresponding to lift up is $+60^\circ$ and the maximum swing angle ($\theta$) of the legs is $\pm 15^\circ$.
during walking as shown in Figure 15. The sampling time is 10 ms. The speed of the legged robot is constant during walking (5.40 cm/s).

**Real design of the single actuator eight-legged walking ROBOTURK SA-2**

A physical prototype was constructed based on the CAD model to save time and reduce equipment damage and faults after full verification by realistic 3D animation of the CAD model by using COSMOSMotion program.
The overview of the prototype of the legged robot is shown in Figure 16. The legged robot has been equipped 24 V battery as a power supply, a Siemens SIMATIC PLC device as a controller and three mechanical switches as a sensor. The equipment and devices installed on the board of the legged robot are indicated in Table II.

The PLC block diagram and the power supply mounted to the legged robot are shown in Figure 17. One 12-V DC gear motor with their power and control systems on board are used for the legged robot. DC gear motor is always the active state during the walking of the spider robot. It provides translating forward and backward motions to the right/left connecting rods and transmission bars in each revolution of DC motor. That is, the right transmission bar moves forward as $+0.02\,\text{m}$ whereas the left transmission bar moves backward as $-0.02\,\text{m}$.

**Figure 13** Body and left-side legs of ROBOTURK SA-2 workspace

**Figure 14** The legs directions during the walking

**Figure 15** Leg geometry and schematic model of a spider leg including their axes of rotation

**Figure 16** The top view of the prototype

**Table II** Equipments of the legged robot

<table>
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<th>Count</th>
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<td>PLC</td>
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</tr>
<tr>
<td>Actuator</td>
<td>1</td>
</tr>
<tr>
<td>Power unit</td>
<td>1</td>
</tr>
<tr>
<td>Sensors</td>
<td>16</td>
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</tbody>
</table>

Controller device

DC gear motor

24 V for PLC power

Mechanic switch (start/stop)

Potentiometer
(Figure 7). Besides, Geneva mechanism rotates only 120° in each revolution of DC motor. Then, the CAM mechanisms are driven by the Geneva mechanism. Movement of the Geneva mechanism (120°) provides the right and left CAM mechanisms rotate one revolution. This work flow causes becoming the walking cycle of the spider robot (Figure 3).

**PLC control of the eight-legged spider robot**

Two mechanic switches are used as input sensors for the single actuator eight-legged walking robot. Only one DC gear motor drives the robot legs, based on obtaining the signal from two mechanical switches. S7-200 Siemens Micro PLC set is used to control the legged robot. The STL diagram, shown in Table III, has been prepared for the straight tetrapod gait of the legged robot. After that, the STL diagram has been loaded to the PLC set from the PC. This program controls the DC gear motor by means of the mechanical switch signals. The inputs and output installed on the STL diagram are indicated in Table IV.

The system with two inputs and one output has an open-loop control as shown in Figure 17 and Table IV. The positive and negative directional rotations of DC gear motor realize both the forward and backward walking of the spider robot. The input addressed with I0.0 represents start button and the other input addressed with I0.1 represents stop button. The only one output element is DC gear motor. Furthermore, the rotation with the counter clockwise (ccw) direction of the shaft of the DC gear motor is represented by Q0.0 whereas Q0.1 introduces the clockwise (cw) direction one. For this reason, two DC motors are indicated in Table IV however they represent the ccw and cw directions of rotation of the only one DC motor. In addition, the output addressed with M0.0 introduces a numerical command connecting the lines each other in the STL diagram.

**Experimental results**

The numerous physical experimental jogging runs of the spider robot (30 × 37.5 × 20 cm) shown in Figures 2 and 16 have been performed in this experimental study. The potentiometers as a sensor have been used to measure angular displacement of each leg both in the x- and y-axes. Besides, analog/digital converter (NEMA4X-SCADA) and digital oscilloscope (FLUKE43B) have been used to gather the measured angular displacement data. Then, the obtained data have been presented in graphical form.

The bottom half of Figures 18 and 19 show the typical sequence of leg contact conditions. To make more understandable, this part of the figure consists of top view and side views of the conceptual diagram. The tetrapod legs start to liftoff in the first interval. Then, the legs perform floating and followed by an interval of touching down. At the end, the interval of the fixed tetrapod stance of the next step occurs. The top half of the figure shows the relation between these four phases and leg positions, obtained the gathered data from the potentiometers located to the legs.

At the end of measuring at 1 KHz averaged over 25 experimental runs, Table V indicates the average times of four phases and the total time in one complete stride. Table V (Saranli et al., 2001; Koditschek et al., 2004) has been motivated and obtained by using Figures 18 and 19. Further, the time-step diagram of the spider robot is shown in Figure 20 (Barfoot et al., 2006; Porta and Celaya, 2004; Barai and Nonami, 2007; Thiry et al., 2004; Durr et al., 2004).

**Conclusion**

The developed legged robot in this study is based on resembling much or less spider leg mechanism. One DC gear motor has only been used to get the straight tetrapod gait. Using the minimum number of actuators makes the light structure possible and simplify the control problem. Increasing power consumption and complexity of the control systems depending on number of the used actuators are well known. To disappear the mentioned problems, special mechanisms can be used. The Geneva mechanism, the CAM mechanisms, the connecting rods and springs used in our design made the number of actuators decrease thus the control of the spider robot eased and its cost also decreased. Table VI compares the features of the presented robot to those in the literature in terms of number of actuator, leg number and speed. This table concludes that the speed of the presented robot is reasonable in the existing leg robots in the literature. In order to save trial-error time and faults, first, the design was modeled on solid works and the animation was realized on COSMOSMotion. Based on the developed model, the prototype of the single actuator eight-legged walking spider-like robot was built. The control of the systems was realized by using PLC.
Figure 18 Four intervals gathered from the physical walking insect robot experimental data

Figure 19 The four following intervals during the \( i \)th tetrapod stride \( S(i) \), with data plotted in the upper figure showing the relation between leg angular positions

Table V  Experimental phase relations in insect robot tetrapod gait

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<tr>
<th>Phases</th>
<th>Phases in one complete stride</th>
<th>Average time (s)</th>
<th>Percentage of time</th>
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<tr>
<td>Quadruped stance (touchdown transient to wait)</td>
<td></td>
<td>0.82</td>
<td>45.05</td>
</tr>
<tr>
<td>Liftoff transient</td>
<td></td>
<td>0.18</td>
<td>9.89</td>
</tr>
<tr>
<td>Quadruped stance forward</td>
<td></td>
<td>0.64</td>
<td>35.16</td>
</tr>
<tr>
<td>Touchdown transient</td>
<td></td>
<td>0.18</td>
<td>9.89</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1.82</td>
<td>100.0</td>
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</tbody>
</table>
As a result, using intelligent biologically inspired walking robots have great potential for in inaccessible and dangerous places to humans and currently available equipments. Studies on biologically inspired robots will increase to improve the actual performance of the designed walking robots in the near future.

**References**


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