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Motion mechanism and gait planning of a wheeled micro robot

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Abstract: Based on a novel shape memory alloy (SMA) actuator, a micro worming robot is presented. The robot adopts a wheeled moving mechanism. The principle of the robot's enlarged pace is introduced, and the structure and motion mechanism of the SMA actuator and the wheeled moving mechanism are discussed. The gait about the robot's rectilinear movement and turning movement is also planned. Under the effect of the eccentric wheel self-locking mechanisms and changing-direction mechanisms, the robot can move forward and backward, and turn actively, which overcomes the disadvantages of the traditional SMA micro robots to a certain extent. Furthermore, some experiments on the heating current of the SMA actuator and the robot's motion capability are carried out.

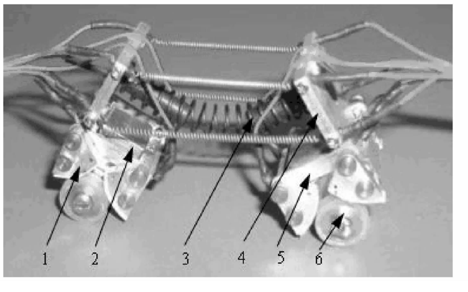
Key words: micro robot; shape memory alloy actuator; wheeled; gait planning

The shape memory alloy (SMA) actuator is one kind of novel actuators. In some cases, it can replace conventional actuators (such as motor, air cylinder). Compared with other novel actuators (such as piezoelectric actuator, electromagnetic actuator), the SMA actuator has some advantages: higher power/weight ratio, simpler structure, no noise or pollution[1]. At present, many micro robots based on the SMA that can be used in industrial and medical fields have been presented[2-7]. Most of them adopt legged or worming structure. Because of the restriction of material characteristics of the SMA, the robot structure and moving mode, these SMA robots have a common disadvantage: their moving speeds are very low, which limit their application range to a great extent. To overcome this disadvantage, research on novel SMA material and walking mechanisms is imperative.

An SMA actuator is introduced in this paper. The actuator can not only shrink and stretch along its axis, but it can also bend in any direction. Based on this SMA actuator, a rigid/elastic coupling micro wheeled robot is presented. Compared with the robots introduced in the above documents, the moving pace and speed of this robot are greatly increased. Furthermore, eccentric wheel self-locking mechanisms and changing-direction mechanisms control the robot's moving direction and realize its bidirectional movement.

1 Robot Mechanisms

The wheeled robot consists of five parts: left car body and right car body, two elastic rubber bands, two SMA actuators, changing-direction mechanisms, eccentric wheel self-locking mechanisms and wheels. Its net weight is 21 g, and the dimension is 40 mm × 18 mm × 25 mm. The robot's configuration is illustrated in Fig. 1.

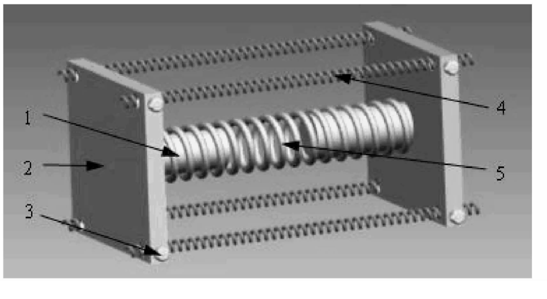


1—Eccentric wheel; 2—Balance weight; 3—SMA actuator; 4—Car body; 5—Changing-direction mechanism; 6—Wheel

Fig. 1 Configuration of the wheeled robot

1.1 SMA actuator

The configuration of the SMA actuator is illustrated in Fig. 2. The SMA actuator is one kind of bias double-passage actuators[8]. It consists of one ordinary helical spring, SMA helical springs, guide bars, baffles and retaining screws.



1—Guide bar; 2—Baffle; 3—Retaining screw; 4—SMA helical spring; 5—Ordinary helical spring

Fig. 2 Configuration of the SMA actuator

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The ordinary helical spring is put outside the guide bars, and the guide bars are fixed to the center of the baffles. The SMA helical springs are installed in rectangular parallelepiped and their ends are clamped by the retaining screws. We can see that this SMA actuator has a characteristic: it can shrink along the guide bars when all the SMA springs are heated, and can bend in any direction when one or two SMA springs are heated.

In the SMA actuator, the ordinary spring is always in compression state and the SMA spring is always in extension state. At room temperature, the stiffness coefficient of the ordinary spring is much larger than the SMA spring and the SMA actuator is in stretching state. After heating, the stiffness coefficient of the SMA spring will become larger, which will overcome the stretching force of the ordinary spring and make the SMA actuator shrink. After cooling, the SMA spring will go back to its initial state and the SMA actuator will stretch under the stretching force of the ordinary spring.

The SMA actuator's structure can enlarge its moving pace greatly (see Fig. 3).

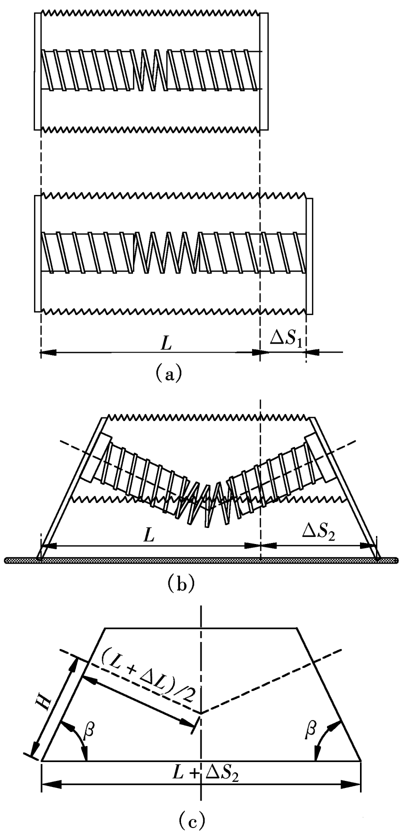

Fig. 3 Schematic diagram of enlarged pace

Like the traditional SMA robots, we assume that the SMA actuator can only shrink and stretch along its axis. At room temperature, the SMA actuators are in stretching state and have the maximum length. After heating, the SMA actuators will shrink and become shorter. In the process, the displacement of the SMA actuators is ΔL. We can see that ΔL is just the robot's moving pace ΔS_1, that is, $\Delta S_1 = \Delta L$.

In this SMA robot, the SMA actuator can not only move along its axis, but can also bend down when the upper SMA springs are heated, which will incline the car bodies. From Fig. 3(b), we can see that the wheeled robot's moving pace ΔS_2 is much larger than ΔS_1 when the displacement of the SMA actuators is also ΔL.

Fig. 3 (c) is the deforming schematic diagram of the SMA actuator. The approximate expression of ΔS_2 is

$$\Delta S_2 \approx 2H\cos\beta + (L + \Delta L)\sin\beta - L \qquad (1)$$

where $L + \Delta L$ is the length of the SMA actuator; H is the installing height of the SMA actuator in the robot; and β is the angle between the car body and the ground.

1.2 Eccentric wheel self-locking mechanism

In common wheeled robots, wheels are driven by motors. So these robots can realize bidirectional movement easily. In this wheeled robot, the SMA actuator's stretching and shrinking has no directivity. When it stretches or shrinks, the robot's wheels cannot turn in the same direction. Thus the robot cannot go ahead.

To realize forward or backward movement, the wheels of one car body must be locked when the SMA actuator stretches or shrinks, which will provide motion fulcrum for the other wheels and convert the SMA actuator's bidirectional movement to the robot's one-directional movement. So a suitable wheel locking device should be installed on the robot. Furthermore, to realize its bidirectional movement, the robot also needs changing-direction mechanisms.

We adopted an eccentric wheel self-locking mechanism as a wheel locking device (see Fig. 4). The arrow indicates that the robot is moving left.

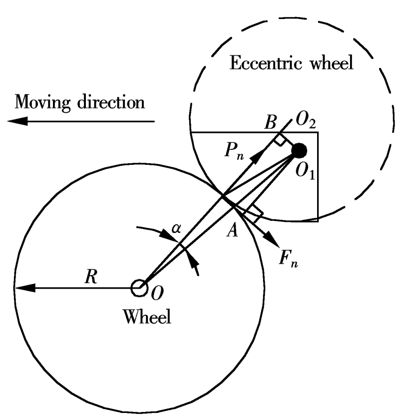

Fig. 4 Eccentric wheel self-locking mechanism

When the wheel tries to turn anticlockwise (left), the eccentric wheel will make a pure rolling clockwise against the wheel under the effect of the friction force between the wheel and the eccentric wheel. The clamp force between them will become smaller and smaller. So the resisting force of the eccentric wheel to the wheel can be ignored. The wheel can turn left freely under this condition.

When the wheel tries to turn clockwise (right), the eccentric wheel will turn anticlockwise because the direction of the resultant force (composed of P_n and F_n) is below the rotation axis of the eccentric wheel. The clamp force between the wheel and the eccentric wheel will increase in the process. Finally, the eccentric wheel remains static against the wheel, which means that the wheel is fixed to the car body and the friction between the wheel and the ground changes from rolling friction to sliding friction. Experiments show that the sliding friction force is large enough to prevent the wheel from turning against the ground. In this way, the eccentric wheel self-locking mechanism successfully keeps the robot's wheels from turning backward when the robot moves ahead.

The self-locking condition for the eccentric wheel self-locking mechanism is

$$\left.\begin{aligned} F_n \times \overline{O_1A} > P_n \times \overline{O_1B} \\ F_n = P_n \times f \end{aligned}\right\} \tag{2}$$

and

$$\frac{\overline{OO_1}\sin\alpha}{\overline{OO_1}\cos\alpha - R} < f$$

where f is the friction coefficient of the contact surface.

1.3 Changing-direction mechanism

There are two eccentric wheels installed on both sides of each wheel, which constitute double eccentric wheels self-locking mechanism. The function of the changing-direction mechanism is to make one eccentric wheel contact the wheel and another eccentric wheel disengage the wheel according to the moving direction.

There are four changing-direction mechanisms installed on the car bodies. They control the eccentric wheels of four wheels respectively. The changing-direction mechanism is actually a parallelogram mechanism above the eccentric wheels (see Fig. 5). The rocker and the eccentric wheel below it are rigidly connected.

Every changing-direction mechanism is driven by an SMA helical spring and an ordinary torsion spring. Fig. 5 is the diagrammatic sketch of a changing-direction mechanism on the left car body. The torsion

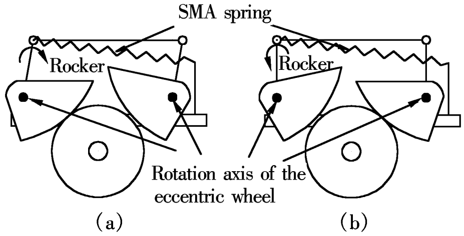

Fig. 5 Changing-direction mechanism on left car body. (a) Move right; (b) Move left

spring is installed on the rotating axis of the left eccentric wheel and its two ends are fixed to the car body and the eccentric wheel respectively (the torsion spring is not marked in Fig. 5). One end of the SMA spring is connected to the connection shaft of the rocker and the connecting rod. The other end is connected to the car body.

In the initial state (at room temperature), the SMA spring is extended by the torsion spring. And the right eccentric wheel contacts the wheel and left eccentric wheel disengages the wheel (see Fig. 5 (b)). The robot can only move left under this condition.

When the SMA spring is heated, its stiffness coefficient becomes larger and the SMA spring will shrink, which will make the rocker rotate clockwise. Thus the parallelogram mechanism and the two eccentric wheels will rotate clockwise. So the left eccentric wheel contacts the wheel and the right eccentric wheel disengages the wheel (see Fig. 5 (a)). Now, the robot can only move right.

After the SMA spring is cooled, its stiffness coefficient becomes smaller. Under the effect of the torsion spring, the rocker will rotate anticlockwise, which will make the parallelogram mechanism and the two eccentric wheels rotate anticlockwise. The robot goes back to its initial state (see Fig. 5 (b)).

2 Gait Planning

The wheeled robot's special structure determines its particularity in moving. The following will show the robot how to realize its rectilinear movement and how to turn.

2.1 Rectilinear movement

A period of motion of the robot can be divided into three processes. In Fig. 6, the robot is moving right (Right eccentric wheels disengage wheels and left eccentric wheels contact wheels). Fig. 6 (a) is the robot's initial status and the SMA actuators are in stretching state. The SMA springs mentioned below are the SMA springs of the SMA actuator.

1) The upper SMA springs are heated and the lower SMA springs keep their initial status. The ordinary spring begins to bend. Under the effect of the

eccentric wheel self-locking mechanisms, the left wheels remain static against the ground. The right wheels roll right. The robot changes from status (a) to (b). In this process, the right wheels move right for a distance of S_1.

2) Both the upper SMA springs and the lower SMA springs are heated. The ordinary spring is compressed. Under the effect of the eccentric wheel self-locking mechanisms, the right wheels remain static against the ground. The left wheels roll right. The robot changes from status (b) to (c). In the process, the left wheels move right for a distance of $S_1 + S_2$.

3) All the SMA springs are cooled and the ordinary spring begins to stretch. Under the effect of the eccentric wheel self-locking mechanisms, the left wheels remain static against the ground and the right wheels roll right. The robot changes from status (c) to (d). In the process, the right wheels move right for a distance of S_2.

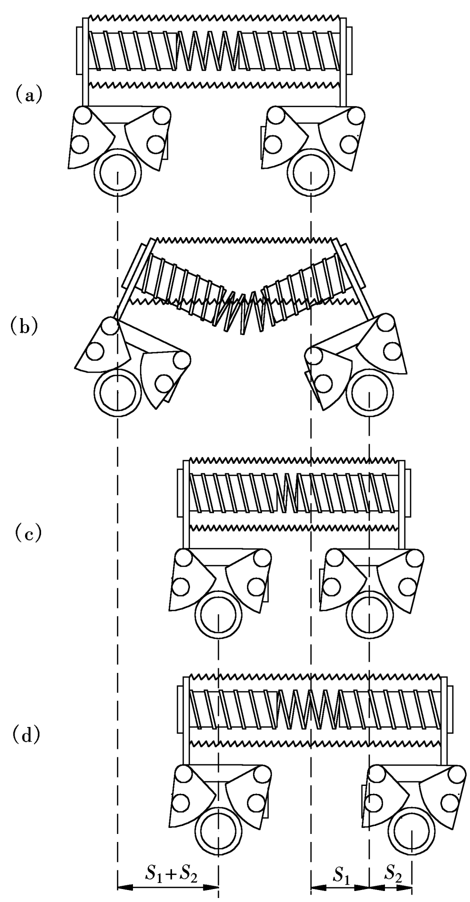

Fig. 6 Diagrammatic sketch of right movement

2.2 Turning method

The robot will realize its turning when the right or left SMA springs are heated at the same time. In Fig. 7, the robot is moving ahead along the *y* axis before turning right: ① Let the SMA actuator be in stretching state (a). ② The left two SMA springs are heated, and the ordinary spring begins to bend. Under the effect of eccentric wheel self-locking mechanisms, the front wheels keep static and the back wheels move forward with sliding and rolling. The robot changes its status from (a) to (b). ③ Both the right SMA springs and the left SMA springs are heated. The ordinary spring is compressed. Under the effect of eccentric wheel self-locking mechanisms, the back wheels keep static and the front wheels move backward with sliding and rolling. The robot changes its status from (b) to (c). ④ All the SMA springs are cooled and the ordinary spring begins to stretch. Under the effect of eccentric wheel self-locking mechanisms, the back wheels keep static and the front wheels move forward with sliding and rolling. The robot changes its status from (c) to (d). Thus the robot realizes a turn of a certain angle.

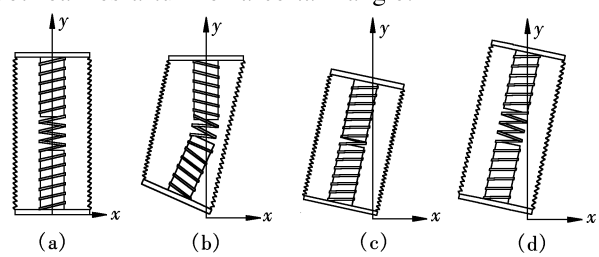

Fig. 7 The wheeled robot is making a right turn

3 Experiments Analysis

Main parameters of the SMA actuator used in the wheeled robot are as follows: ① The ordinary spring: the average diameter of spring is $\phi 5$ mm, the diameter of spring thread is $\phi 0.6$ mm, and the number of effective coils is 18, made with 1Cr18Ni9Ti. ② The SMA spring: the average diameter of spring is $\phi 1.5$ mm; the diameter of spring thread is $\phi 0.3$ mm; and the number of effective coils is 69, made with TiNiCu10at%.

Deforming characteristics of the SMA actuator are evaluated in air at 20° and with no load. Fig. 8 shows the relationship between the response time of the heating process of the SMA actuator and the current. When the current is lower than 300 mA, the response time is too long, which will slow the robot's moving speed greatly. When the current is above 700

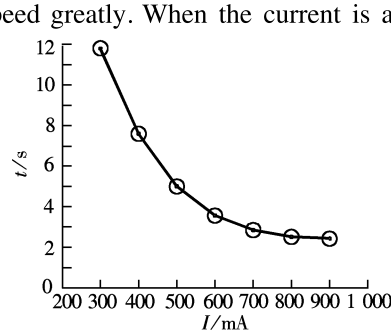

Fig. 8 Response time of the SMA actuator at different currents

mA, the response time is lower than 3 s. When the current is greater than 800 mA, the deforming can, apparently, not speed up. In order to reduce power consumption and obtain a higher moving speed, we choose a heating current of 800 mA.

Fig. 9 shows the effect of the SMA actuator's structure in increasing the robot's moving speed. The lower curve is the time-displacement curve of the robot when the SMA actuator only shrinks and stretches along its axis. The upper curve is the time-displacement curve of the robot when the actuator moves as described above. We can see that the latter speed is nearly twice that of the former speed. To a certain extent, it can be regarded as a compensation for the SMA actuator's disadvantage of long responding time.

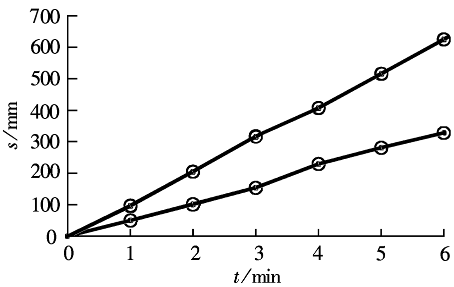

Fig. 9 Effect of the SMA actuator in increasing robot's speed

4 Conclusion

The volume of the robot is very small. So it can be used in some special cases, such as the detection and maintenance in fine pipes or narrow gaps in nuclear power plants with micro sensors, micromanipulators, CCD cameras or other equipment installed on the robot. Now, we have to use external power supply because the power consumption of the SMA actuators is very high, which reduces the robot's motion capability. This problem will be solved in the future with the development of battery technology. The robot's power supply in Ref. [4] is replaced by a kind of novel battery. Although the battery will be used up in 18 min, the robot's motion capability is improved greatly.

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轮式微型机器人运动机理与步态规划

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摘要:在一种新型形状记忆合金驱动器的基础上,研制了一种微型蠕动机器人,该机器人采用轮式移动机构. 对形状记忆合金驱动器、轮式移动机构的结构和运动机理以及机器人的步距扩大原理进行了讨论. 并在此基础上,对机器人的直线运动步态和转弯步态进行了规划,使机器人在偏心轮自锁机构和换向机构作用下,不但可以前后运动,还具有主动转弯能力,在一定程度上克服了传统的形状记忆合金机器人移动速度慢、只能被动转弯的缺点. 最后对形状记忆合金驱动器所需加热电流及该机器人的运动性能进行了试验分析.

关键词:微型机器人;SMA 驱动器;轮式;步态规划

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