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# Deformable-wheel Robot based on Soft Material

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*Soft robotics, a concept contrary to conventional "hard" robotics, is a robot design methodology that uses soft materials inspired by nature. In contrast to a hard robot, a soft robot is composed of soft and flexible materials that blur the distinction between an actuator and a structure, which leads to unique characteristics that cannot be found in a conventional hard robot. This paper presents our approach to the issues that arise when the concept of soft robotics is applied to a wheeled robot. The compliance of the wheel diversifies its potential movement and allows for a high degree of adaptability to the environment. Although the wheel radius of the robot is 50 mm, it can pass through a 30 mm gap and climb a 45 mm step. While soft robotics displays properties whose performance can be challenging to implement, it also enables us to create complex forms of movement in a cheaper and simpler way. We expect that this kind of approach can provide a new design method for a deformable wheel.*

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## 1. Introduction

Soft robotics, a concept contrary to conventional "hard" robotics, is a robot design methodology inspired by natural. A hard robot, which is usually composed of rigid links and joints, displays a strict separation between structure and actuator. In contrast, a soft robot is composed of soft or flexible materials that blur the distinction between the two, which gives it unique characteristics that cannot be found in a conventional hard robot.[1]

Soft robotics can also be a cheaper and simpler way to design a complex movement, and it allows for a more robust design under impact. It can also display a movement that is highly adaptable to different environments. Although soft materials involve some uncertainty and cannot offer the high strength that is offered by rigid materials in conventional robotics, their unusual characteristics are sufficient to fascinate many researchers. Indeed, various research projects have explored the use of such soft materials.[2-9] Applying the idea of soft robotics to a wheel can add new functionality to a wheeled robot. In a hard robot, the scale of its wheels is the dominant factor in determining its ability to traverse rough terrains. If "softness" is applied to a wheel, it becomes possible for this limitation to be reduced. Correll *et al*. realized this concept using an elastic material and pneumatic actuation.[10] Sequential expansion of a segmented part of a wheel created a circular shape that allowed for a crawling movement. Torres *et al*. used a shape memory alloy (SMA) actuator in both the linkage and actuation and it was used in a crushed wheel shape.[11] Variations in the wheel shape made the wheel adaptable to crawling. Sugiyama and Hirai used an SMA coil spring actuator for this same purpose.[12] An SMA coil spring pulled the wheel, which caused it to assume an oval shape. Sequential actuation of the SMA coil then gave it the ability to perform a crawling movement.

In this paper, a deformable-wheel robot equipped with a hybrid system that combines a wheel deformation movement and a wheel rotation movement powered by an electric motor is presented (Fig. 1). The deformation of the wheel gives it a high adaptability to the environment, such as being able to pass through a small gap or climb a high step. By combining this functionality with that of a conventional

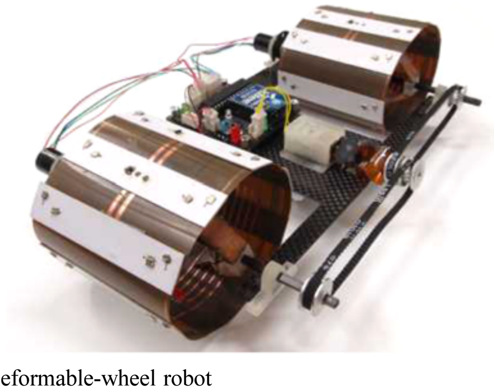

Fig. 1 Deformable-wheel robot

wheel, a robot can move fast on a flat terrain and adapt to a more challenging environment when needed.[13]

There are a number of critical issues involved in realizing this concept. The first is the actuation of a structure with a high degree of freedom. The compliance of the structure induces many degrees of freedom, which usually requires a large number of actuators. We propose a wheel design that uses an SMA coil spring actuator for deforming and rolling the wheel in its deformed shape. The second critical issue regards the torque transmission as the wheel undergoes changes in its shape. Although the wheel structure can assume various shapes, to provide stable torque transmission, there must be sustainable linkage between the wheels and the drive shaft. To address that, the novel design of a spoke that can transmit the appropriate torque even as the wheel undergoes changes in its shape was proposed. The third issue, fabrication, is quite important in soft robotics. While the wheel must be sufficiently compliant to allow for easy deformation, it must also be sufficient rigid to control and maintain stiffness. To meet these two requirements, the composite that consists of segmented rigid parts and a flexible base part was designed.

## 2. Concept of a Deformable-Wheel Robot

Figure 2 presents a schematic diagram of a deformable-wheel robot. The torque for wheel rotation is transmitted by timing belts, and wheel deformation is achieved by the activation of an SMA coil spring actuator. The wheel has a composite structure that consists of both compliant and rigid material. By making the rigid part overlap the base compliant part, the shape of the wheel can be controlled.

The deformation of the wheel facilitates three different types of movement, each with its unique characteristic and purpose. The first type of movement is normal driving movement. With its hybrid system, the robot can not only deform its wheels but also rotate them using an electric motor. This allows for fast movement in a normal state (Fig. 3(a)). The second is caterpillar-like movement. By the successive activation of the actuator in the wheel, the wheel can achieve a crawling motion, which can enable it to pass through a gap that is smaller than the wheel diameter (Fig. 3(b)). The third type of movement is legged-wheel movement. In this mode, activating one segment of the actuator system changes the wheels into a legged shape, a deformation that enables the robot to surmount obstacles that are taller than the original wheel radius (Fig. 3(c)).

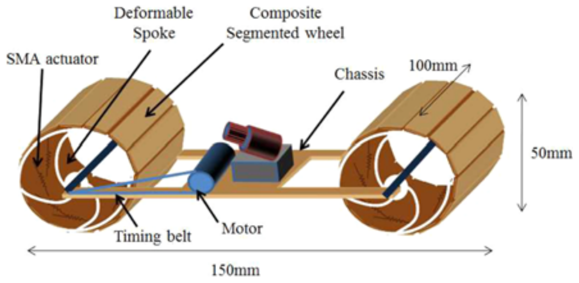

Fig. 2 Schematic of deformable-wheel robot. Wheel deformation is achieved by an SMA actuator, and wheel rotation is produced by an electric motor

## 3. Robot Design

### 3.1 Wheel design

In robot design, the design of the actuation is an essential issue and it represents an even greater challenge in soft robotics because of the compliance of the materials used. In general, the compliance of a structure involves many degrees of freedom, and often requires a large number of actuators. For this reason, an actuator that is simple and lightweight is needed. To address this issue in designing the actuation, we utilized an SMA coil spring actuator.

Figure 4 shows how the actuator functions for each type of wheel movement. The SMA coil spring actuators that are used for shape deformation are bundled in four groups and are activated in each group as a unit. The activation of one SMA group gives the wheels an elliptical shape, and the successive activation of the four groups produces a caterpillar-like movement. In wheel-driving mode, the SMAs are not activated, and in legged-wheel mode, only one group of SMAs is activated.

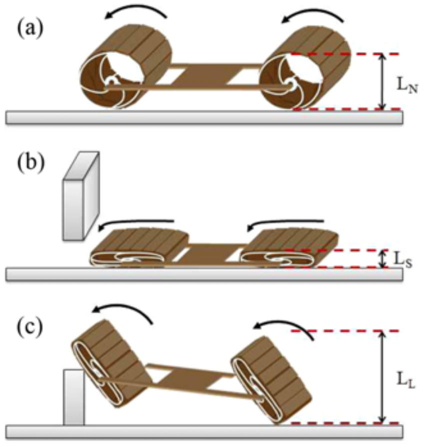

Fig. 3 Three types of movement of the robot: (a) wheel in driving movement, at high speed on flat ground, (b) caterpillar-like movement, passing through a narrow gap by means of SMA actuation, (c) legged-wheel motion, climbing a stair by means of SMA and motor actuation. LN, LS and LL mean a wheel length in normal state, short state and large state each

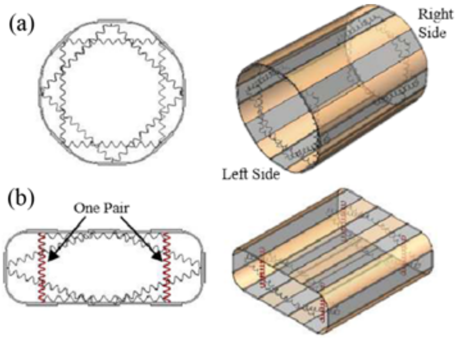

Fig. 4 Eight rigid segments on a wheel and pairs of SMA coil spring actuators attached to each segment for deformation. (a) A total of sixteen actuators are attached to one wheel. The left and the right side of the wheel have four pairs of actuators, respectively. (b) Actuating two pairs at both the left and the right side induces wheel deformation

Since a fair number of SMA actuators were used in the wheel, electrical power transmission to each actuator became an important and thorny problem. In this robot, this problem was solved by embedding a current circuit in the wheel structure (Fig. 5). The details of this technique are discussed in the section on 4. Fabrication. By embedding the current driving circuit in the wheel structure, the current system can innovatively reduce the number of wires that are required, which offers many advantages in terms of robustness and ease of fabrication.

### 3.2 SMA coil spring actuator design

The SMA coil spring actuator amplifies the strain of the SMA wire actuator by winding it in a coil. In general, the maximum permeable strain of the SMA wire is 6-8%. The purpose of a maximum value is to prevent plastic deformation of the SMA and reduce the degradation of the actuator. By winding the SMA wire in a coil, it is possible to use it in a range of more than 100% of its original length. The reduction in the maximum actuation force then represents a trade-off with the amplification of the actuation stroke. However, the SMA still has a high enough power density to actuate soft polymers and micro robots.[14-19] Therefore, an SMA coil spring actuator is suitable for a deformable soft wheel in terms of its high deformation and high power characteristics.

The design methodology of the SMA coil spring actuator entails a procedure for determining three parameters of the coil spring (wire diameter (d), coil diameter (D), and number of coils (n)), thus satisfying the force and stroke requirements in the following two states: contraction and release. In most applications of the SMA coil spring actuator, the modeling of the actuator is developed using a mechanical spring equation that shows the linear force and the displacement relationship.[20,21] However, the SMA has inherent nonlinear tensile characteristics that are produced by stress-induced phase transformation.[22] In this study, a nonlinear 1D model (1)-(2) of the SMA coil spring actuator, driven by the Brinson's SMA model[23] and a mechanical coil spring equation[24] was used. The Brinson's constitutive equation is modified to apply to the coil spring SMA by the mechanical coil spring equation as shown in.[25] The detwinning in the Martensite phase of SMA is expressed by residual strain and the detwinned Martensite volume fraction as the following equations derived in.[25]

$$F_{\mathrm{A}} = \frac{G_A d^4}{8D^3 n}\left(\frac{\cos^3\theta_i}{\cos^2\theta_f(\cos^2\theta_f + \sin^2\theta_f/(1+v))}\right)\delta_{\mathrm{A}} \qquad (1)$$

$$F_{\mathrm{M}} = \frac{G_M d^4}{8D^3 n}\left(\frac{\cos^3\theta_i}{\cos^2\theta_f(\cos^2\theta_f + \sin^2\theta_f/(1+v))}\right)\delta_{\mathrm{M}} - \frac{\pi d^3}{8D} G_{\mathrm{M}} \gamma_{\mathrm{L}} \xi_{\mathrm{S}_\tau} \qquad (2)$$

Here, $F_A$, $F_M$, $\delta_A$, and $\delta_M$ are the force and displacement; $G_A$ and $G_M$ are the shear modulus of SMA in austenite (A) and martensite (M) phase, respectively; $\theta_i$ and $\theta_f$ are the initial and final pitch angles of the coil spring, respectively; $v$ is the Poisson's ratio (0.3); $\gamma_L$ is the maximum residual strain; and $\xi_{S_\tau}$ is the detwinned martensite fraction.

The wheel flexure is assumed as a simple beam model.[26] Based on this model, the required actuation force and displacement of the actuator are calculated as 1.5 N and 14 mm. In order to satisfying these requirements, single coil parameters are determined to satisfy the force requirement and shear strain limitation (0.8).[25] After determining the single coil parameters (d, D), the number of coils (n) is computed for producing actuation displacement. The determined parameters are a 300 μm wire (d), a 2 mm coil diameter (D), and 7 coils (n).

Table 1 SMA property data

| Properties | Experimental Value |
|---|---|
| Austenite Shear Modulus ($G_A$) | 11.26 GPa |
| Martensite Shear Modulus ($G_M$) | 5 GPa |
| Wire Dia. (d) | 300 μm |
| Coil Dia. (D) | 2 mm |
| Coil Number (n) | 7 |

### 3.3 Torque and power transmission mechanism design

For a hybrid system, it is necessary to link the wheel with the motor. The assembly of the compliant wheel structure with a conventional motor system, however, faces a daunting obstacle because of the various shapes of the wheel structure. To maintain the connection between the wheel structure and the motor system, the spoke must be designed such that it can support the different shapes that the wheel can assume, as shown in figure 6. For it to possess this characteristic, a universal joint structure is required, but conventional mechanical parts are not appropriate for our robot because of its weight and complexity.

In this robot, then, a newly designed spoke was adopted. A spherical six-bar linkage based on a two-dimensional structure was designed based on the principle of origami (Fig. 7). By folding a flat sheet along six folded lines, the structure can have three degrees of freedom and is

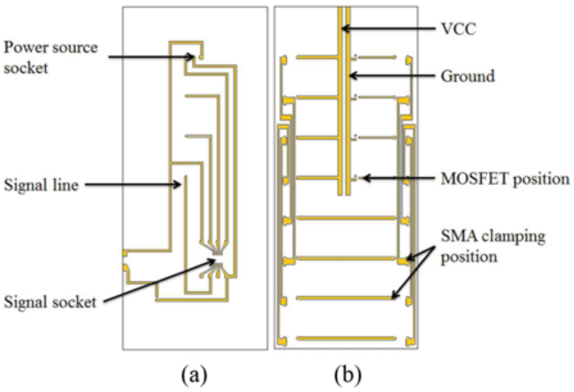

Fig. 5 Embedded circuit design for deformable wheel: (a) inner surface, and (b) outer surface

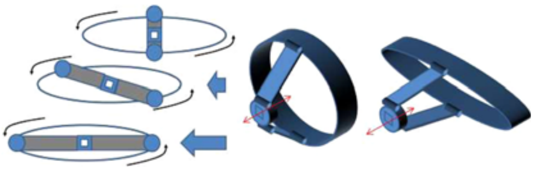

Fig. 6 Various shapes of the wheel. The spoke design must be able to support the different shapes of the wheel[27]

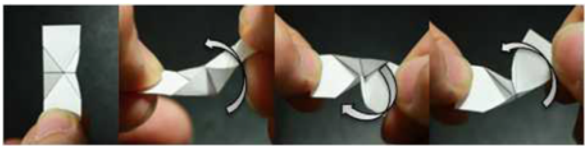

Fig. 7 Spherical six-bar joint based on two-dimensional structure. The structure has three degrees of freedom[17]

conformable to various shapes of the wheel.[27] The combination of the spherical six-bar joint with an axial sliding mechanism guarantees a reliable connection in whatever shape the wheel may assume. The entire structure of the stroke assemblage is shown in figure 8.

The problem of power transmission to a rotating structure was solved by adopting a slipring, which is a mechanical component that electrically links a rotating part with a non-rotating part. A geared DC motor was used for the wheel rotation. The motor model is a D&J WITH's RA-12WGM Series with a gear ratio of 1/298. The torque of the motor is transmitted to the wheel by a timing belt.

### 3.4 Steering mechanism design

In order for the robot to steer, a modified pivot steering mechanism was devised. Because it is almost impossible to steer either a front wheel or a rear wheel of the robot, an additional part that can be used as a pivot that helps the robot turn its body on that point is needed for steering. Furthermore, this additional part has to be as simple, lightweight, and efficient as possible.

The proposed steering mechanism in figures 9, 10 shows how the steering part is actuated and helps the body to rotate. Two of these parts are connected to both the left and right side of the body. The design of the steering mechanism was derived from that of a jack (Fig. 10). As the SMA coil spring actuator attached to the lower links is heated by electric power, the two links get closer to each other and trigger a large vertical displacement.

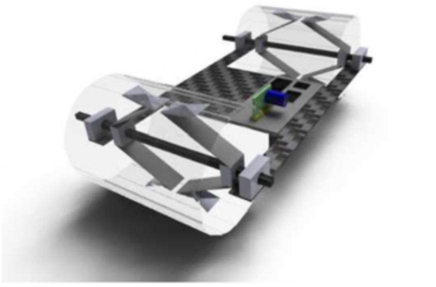

Fig. 8 Spoke structure for deformable wheel

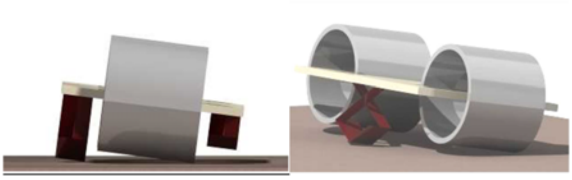

Fig. 9 Concept of steering mechanism. When the jack is extended, it hinders the mechanism's movement and causes a steering movement of the robot

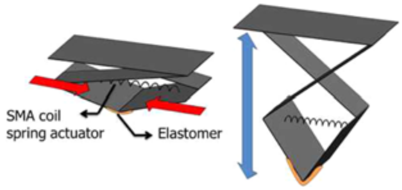

Fig. 10 Steering jack mechanism. This mechanism acts as pivot when the robot needs to steer in a given direction

## 4. Fabrication

### 4.1 Wheel fabrication

In designing the locomotion of soft robot, body structure design is a key issue along with the actuation method, because the movement of a soft robot is the result of interaction of the actuator with the structure. Each component of the structure, i.e., the composition, material, geometry, etc., performs an important role in the design. In our fabrication of the body structure, a Smart Composite Microstructures (SCM) process with laser machining was applied in bigger scale (Fig. 11).[28] Rigid films and flexible films are cut into designed pattern by the precision laser. These patterned film is laminated in high temperature and pressure. Finally, the flexible linkage structure is developed as the right side figure in Fig. 11.

In order for it to have a deformable structure, the wheel must have flexible components. A flexible structure, however, usually involves a high degree of freedom, so a number of constraints (rigid components) are also needed for control of the shape of the wheel. This twofold property was attained by using a composite of mermaid paper and kapton-copper film. Mermaid paper was used for the rigid components, and kapton-copper film for the flexible component. Kapton-copper film was used to make the embedded circuit for electrical power transmission. With a composition of flexible components with segmented rigid components, the structure is able to act as a linkage and joint of a mechanical system.

The mermaid paper that was used for the rigid segments of the wheel was trimmed by laser machining. The other part of the wheel, the circuit embedded kapton film, was made by an etching process. First, the kapton tape was attached to the copper part of the kapton-copper film. Next, the kapton tape was cut into the circuit pattern using a laser machine, and the kapton tape was removed, except where it

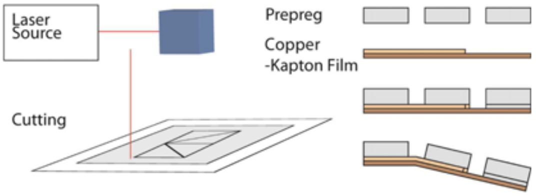

Fig. 11 Schematic diagram of fabrication of composite composed of a segmented rigid part with flexible base part[28]

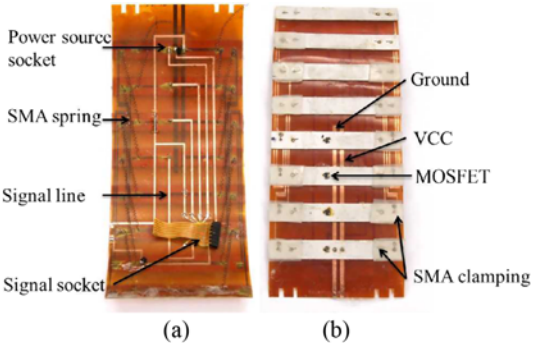

Fig. 12 Fabrication result of the wheel structure. The wheel includes a signal and power line, which makes for a much simpler structure, even though many SMAs are controlled

covered the circuit line. In the etching process used on the film, the part of copper that was covered with kapton tape remained, and the other part of copper was removed in a manner that is quite similar to the PCB process. The copper part that remained became the circuit line. The process of laminating these materials was done with a paper-coating machine, by applying heat and pressure. Figure 12 shows the result of the wheel fabrication process.

### 4.3 Spoke fabrication

The spoke structure was fabricated in a way similar to that used in the wheel fabrication process. The significant differences between the two processes are that kapton film was used instead of kapton-copper film for the flexible component and that a glass fiber was used instead of mermaid paper for the rigid component. Although it is much easier to cut mermaid paper into a desired pattern than to cut glass fiber, glass fiber is stiffer than mermaid paper and also forms a much stronger bond with kapton film because of a resin in the fiber. In the spoke structure, each segment, especially the six-bar linkage segment, is subject to high stress, which causes not only delamination of the composite but also failure of the rigid material. This makes glass fiber a better option than mermaid paper.

The fabrication method is as follows. First, a prepreg of glass fiber on a gel pack was patterned using a laser machining. The gel pack was used for arranging each segment of the spoke. Next, the kapton film was overlapped and cured in a hot press machine. The overlapped layers were cured at 140°C at a pressure of 15 MPa for 5-10 min. The completed structure is shown in figure 13.

### 4.4 Steering jack fabrication

The steering jack must be able to tolerate a much higher degree of stress than the spoke structure because it must be able to bear the weight of the entire robot. To make lightweight and robust links and joints, a process similar to that used in the wheel and the spoke fabrication method was used, which utilizes composites as links and tough polymers as joints. In this structure, carbon fiber reinforced plastic was used for the rigid segment. The lamination process is very similar to that used for the spoke structure, except that the temperature was 170°C. The resulting structure is shown in figure 14.

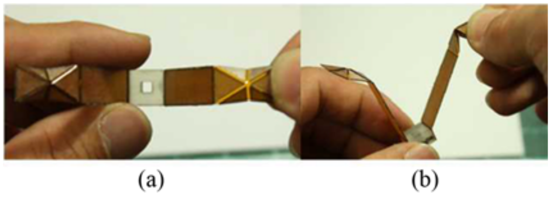

Fig. 13 Fabrication result for the spoke. Glass fiber was used for the rigid component and kapton film was used for the flexible component[27]

Fig. 14 Fabrication result for the steering jack. Carbon fiber reinforced plastic was used for the rigid component and kapton film for the flexible component

## 5. Experimental Results

In the experiment, we tested the robot’s steering ability and three different movements that were specifically designed for driving, passing through a narrow gap, and climbing a high step.

In its wheel rotation motion, the robot can drive at a speed of 12 cm/s. In a test of the robot passing through a narrow gap, all eight nodes in the wheel had to be brought close to each other by successively actuating four pairs of SMA coil spring actuators that are directly attached to the corresponding segments (Fig. 15). Considering the heating and cooling time and the amount of current to be applied to the SMA coil spring, the duty factor of the current was determined, and this mode of actuation was programmed into the chip. During the robot’s passage through a narrow gap, the front and rear wheels both move in a caterpillar-like fashion. The robot, which has a wheel diameter of 50 mm ($L_N$), was able to pass through a gap of 30 mm ($L_S$), which amounts to a 40% degree of deformation.

In another experiment, in which the robot climbs over a high step, only one pair of SMA springs is actuated to maintain the contracted

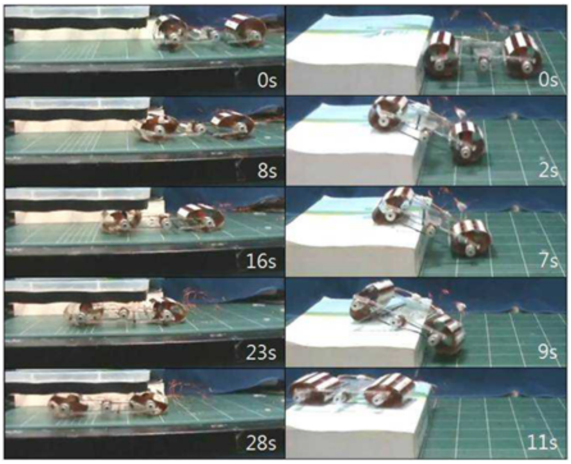

Fig. 15 Experimental results of the deformable wheel. Left still shots show robot passing through a narrow gap and right still shots show robot climbing a high step

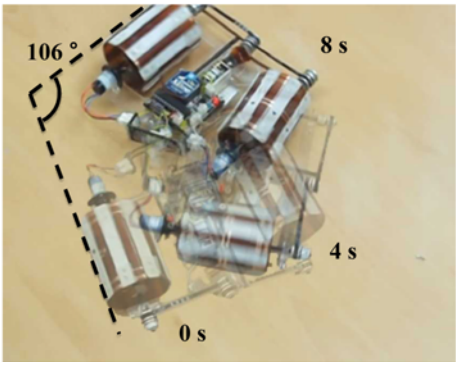

Fig. 16 Experimental result of the deformable wheel in steering motion. Using pivot steering, the robot can steer at speed of 13.3°/s.

length during climbing. When the flat wheels are rotated, they manifest legged-wheel locomotion and can quite effectively climb over a high step as long as the height of the step does not exceed the elongated diameter ($L_L$) of the wheel. In the experiment, the robot was able to climb over an obstacle with a height of 45 mm, which is about 75% of the elongated wheel diameter.

During steering, the robot body is tilted to the opposite side by this vertical force, and it rotates on the axis located at this pivot point because of the friction force between the elastomer and the floor. When the electric supply is cut, the SMA coil spring cools down and the steering part recovers its original shape because of the elastomer, which enables the robot to move forward again. As can be seen in figure 16, the robot rotates on the pivot point even though there is a slight gap between the pivot and the floor. The measured rotation speed of the body was observed to be about $13.3^o$/s.

## 6. Conclusion

This paper has presented approaches to the resolution of some key issues that arise when the concept of soft robotics is applied to a wheeled robot. The compliance of the robot's wheels diversifies its potential movement and allows a high degree of adaptability to the environment, which is hard for a conventional robot to achieve. The wheel radius of robot is 25 mm but it can pass 30 mm gap and climb 45 mm step.

To obtain a compliant but functional structure, the robot's wheels and other components were made using a combination of rigid and flexible materials. The components moved like a mechanical system composed of linkages and joints, in which the rigid part acts as a linkage and the flexible part acts as a joint. Each component was made of a different material suited to its purpose. An SMA coil spring actuator was used for actuation. The compliant structure, which has a high degree of freedom, required many constraints or actuators to provide the needed degree of control. In this robot, a series of SMA actuators was used to control the structure. This was feasible because of the simple, high energy density characteristic of an SMA and the wheel embedded circuit structure.

Still, a number of issues remain to be resolved. The first is related to the actuation. The use of multiple SMA actuators can present a problem. The high energy density and simple structure of an SMA allows for a structure that is not bulky, even with the use of 16 actuators, but a large number of actuators can present problems in manufacturing and control. If we can constrain a number of degrees of freedom, these problems might be resolved. The second challenge to meet regards the degree of robustness. The transmission structure, especially the spoke structure, is prone to breakage when high torque is applied to the wheel. If the characteristics of softness is applied, it is possible to reduce the stress concentration on the spoke and thus reduce the risk of breakage.

Although in some regards, soft robotics involves certain properties whose performance is challenging to implement, it is also true that soft robotics is able to achieve complex movement in a cheaper and simpler way. We expect that this kind of approach can be used as a way to design a functional deformable wheel.

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