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THE DEFORMABLE WHEEL ROBOT USING MAGIC-BALL ORIGAMI STRUCTURE

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ABSTRACT

In this paper, we present a deformable wheel robot using the ball-shaped waterbomb origami pattern, so-called magic-ball pattern. The magic-ball origami pattern is a well-known pattern that changes its shape from a long cylindrical tube to a flat circular tube. By using this special structure, a wheel with mechanical functionalities can be achieved without using many mechanical parts. Moreover, because of the characteristic that the structure constrains its own movement, it is possible to control the whole shape of the wheel using only few actuators. And also, from analysis of the wheel structure in kinematic model, the performance of the wheel and determine the condition for actuators can be predicted. We think that the proposed design for the deformable wheel shows the possibility of using origami structure as a functional structure with its own mechanism.

INTRODUCTION

The word, origami, comes from the traditional Japanese art of paper folding. The unique characteristic of origami that realizes three-dimensional structures from two-dimensional materials have long attracted attention from various fields such as design, education and mathematics [1-6]. Many of today's engineers are using this oriental art to solve problems [7-12]. It can be used as an inspiration to some architectural designs [13], and can also be used as fabrication method of robot design [14, 15] or MEMS process [16, 17]. Furthermore, some researchers have tried to analyze its characteristics, thereby designing and utilizing some patterns as mechanical components [18-20].

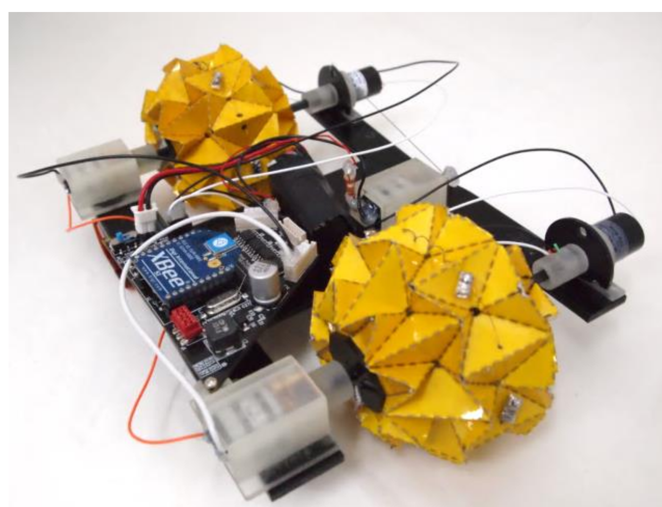

Figure 1. THE DEFORMABLE WHEEL ROBOT

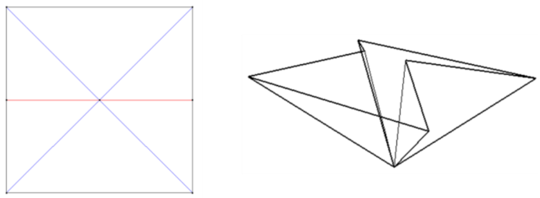

Figure 2. PATTERN OF BASIC COMPONENT (LEFT). BLUE LINE MEANS VALLY FOLD AND RED LINE MEANS MOUNTIN FOLD. ‘ORIPA’ IS USED FOR DESIGN [22]. SHAPE OF THE BASIC COMPONENT DRAWED BY ‘RIGID ORIGAMI SIMULATOR’ [23] (RIGHT).

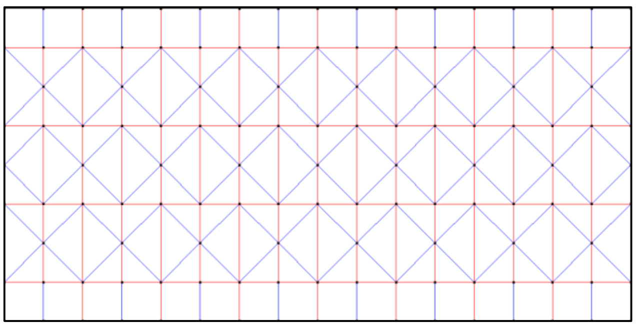

Figure 3. THE PATTERN OF THE ORIGAMI WHEEL STRUCTURE. BLUE LINE MEANS VALLY FOLD AND RED LINE MEANS MOUNTIN FOLD. ‘ORIPA’ IS USED FOR DESIGN [22].

In this paper, a deformable wheel robot using ball-shaped waterbomb origami pattern, so-called magic-ball pattern (Fig. 1) is presented. A magic-ball origami pattern is a well-known pattern that changes its shape from a long cylindrical tube to a flat circular shaped tube. The structure has been used in various applications because of its unique characteristic [10, 14]. A deformable wheel robot can overcome various shapes of terrains by deforming the shape of the wheel [21]. By using this origami structure, the deformable wheel can be built without using many mechanical parts; the wheel is built with a single piece of sheet, with specific folds. Moreover, because of the characteristic that the structure constrains its own movement, it is possible to control the shape of the wheel using only a few actuators, unlike other deformable wheel robots based on a single compliant material. And also, from analysis of the wheel structure in kinematic model, the performance of the wheel and determine the required displacement for actuators can be predicted.

The origami wheel was fabricated by laser machining on paper with polyimide film and deformation of wheel was achieved by shape memory alloy coil spring actuator and passive spring. When the robot run into the small slit smaller than the wheel diameter, the robot can deform the wheel and it is possible to get through the terrain. We think that the proposed design for the deformable wheel shows the possibility of using origami structure as a functional structure with its own mechanism.

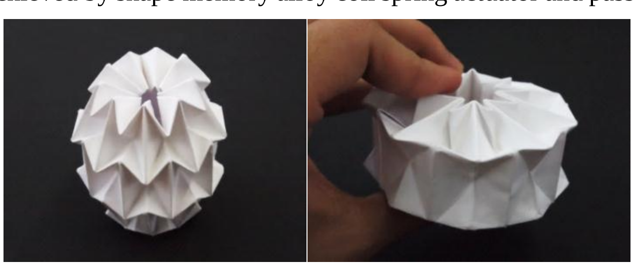

Figure 4. THE ORIGAMI WHEEL STRUCTURE (LEFT). WHEN THE STRUCTURE IS PUSHED, THE RADIUS OF THE WHEEL IS INCREASED (RIGHT).

DESIGN

Wheel structure

The waterbomb pattern is one of well-known origami patterns, which is composed of basic pattern in Fig. 2. Magic-ball pattern is one of the variations of waterbomb pattern which has circular shape made by attaching each end of the pattern. We design deformable wheel using some characteristic of this structure. We use the pattern composed of 3 x 8 basic patterns (Fig. 3) and it shows movement like Fig. 4. When the end point of the wheel is pushed inside, the radius of the wheel is increased.

Spoke Structure

For using this structure as a wheel, a spoke structure which connects the wheel structure with a shaft is needed. Moreover, for deformation of the wheel, the spoke design based on origami which acts as linkage, joint and slider is required. However, the shape of the end point of the wheel in Fig. 4 makes it hard to

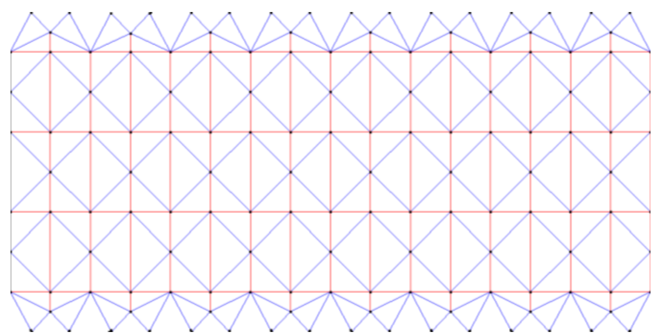

Figure 5. THE PATTERN VARIATION FOR SPOKE STRUCTURE OF THE ORIGAMI WHEEL.

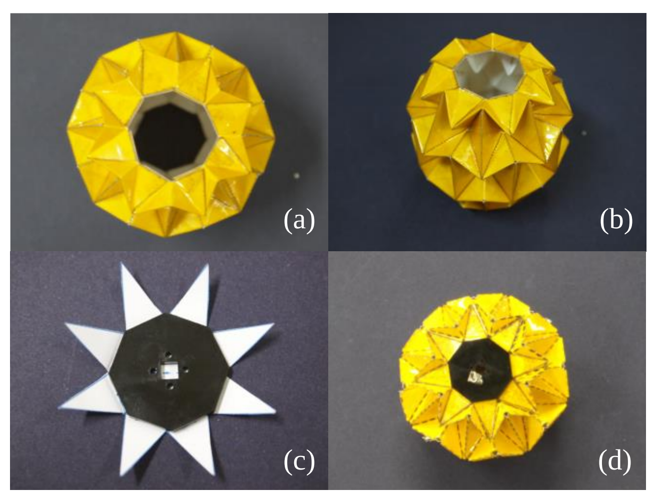

Figure 6. RESULT OF THE SPOKE DESIGN. ASSEMBLED SHAPE OF NEW DESIGN OF THE WHEEL PATTERN (a - b). SPOKE WITH ACRYLIC PLATE (c). FINAL SHAPE OF THE WHEEL (d).

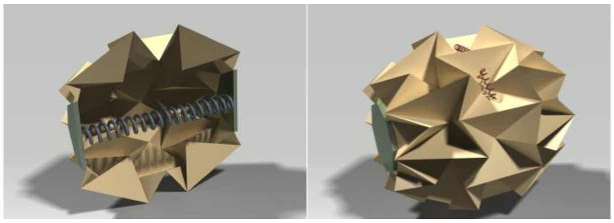

Figure 7. DESIGN OF THE WHEEL ACTUATING MECHANISM. THE ACTUATION OF THE WHEEL REALIZED USING PASSIVE SPRING (LEFT) AND SHAPE MEMORY ALLOY COIL SPRING ACTUATOR (RIGHT).

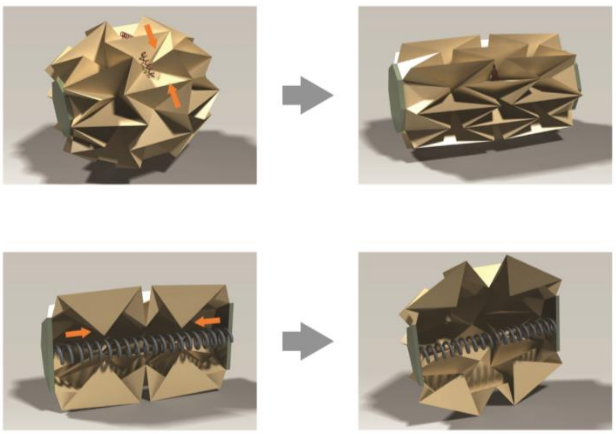

Figure 8. TWO WAY ACTUATION OF THE WHEEL

achieve this function. In other words, the wheel structure and spoke structure have different function and shape from each other. The problem is how to link these two different structures. To solve this problem, intersection of these structures is needed. In this paper, we solved this problem by redesigning the end of the wheel structure pattern as in Fig. 5. The final shape of the folded pattern is in Fig. 6 (a). By attaching other spoke component in Fig. 6 (c), final wheel structure in Fig. 6 (d) is achieved.

Actuation

Deformation. In deformation of the wheel, passive spring and shape memory alloy (SMA) coil spring actuator were used antagonistically. The fact that SMA coil spring actuator has high energy density and simple structure makes it possible to design a simple wheel deforming mechanism. Figure 7 shows the schematic design of the deformable wheel. When SMA is activated by current, it goes through transformation from

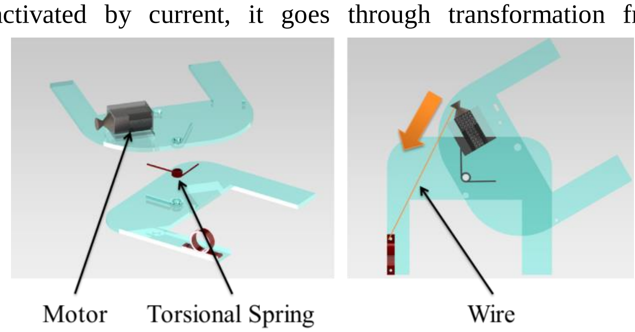

Figure 9. SCHMATIC OF STEERING MECHANISM

martensite to austenite phase and it pulls the surface of the wheel and shrinks the radius of the wheel. When the SMA actuator is cooled by ambient air and its stiffness decreases as it comes back into martensite phase, the passive spring would have enough force to pull the end of the wheel, having the wheel recovers its initial radius.

Driving. Driving motion of the wheel was achieved by electric motor like other ordinary wheeled robot. For current driving in SMA coil spring on the wheel, a slipring, a mechanical component that electrically connects a rotating part with a non-rotating part was used.

Steering. Steering motion is achieved by a torsional spring, an electric motor with gearbox and a wire. When the electric motor pull the wire, the robot steers to the left side and when it releases the wire, the robot steers to the right side by the torsional spring. By using this mechanism, it is possible to achieve enough torque to steering although the shaft of the motor is in horizontal direction with steering axis, which makes it possible to lower the height of the robot. The schematic design for the steering mechanism is shown in Fig. 9.

STRUCTURE ANALYSIS

Modeling of the structure

For analysis the structure of the wheel, each point is named as in Fig. 10. Two assumptions were made for analyzing the structure. First, the structure has a symmetrical shape. Actually,

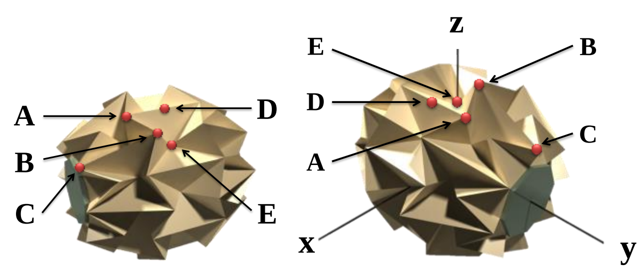

Figure10. POINT NAMING AND COORDINATING FOR THE ANALYSIS OF THE WHEEL

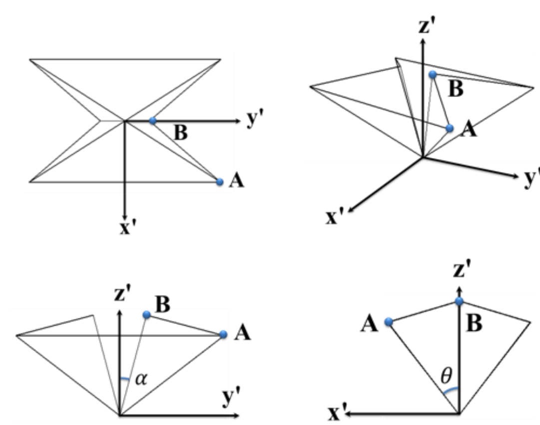

Figure 11. ANALYSIS OF BASIC COMPONENT OF THE WHEEL

this structure could not be symmetrical because forces applied to the structure may not be symmetrical, but for simplicity, we assume that this effect is minor. Second, a folding motion occurs only in fold lines, and facets are always straight. On these assumptions, analysis of the whole structure can be started from analysis of a basic component. Figure 11 shows the basic component of the magic ball pattern. Angle θ and α are defined as in Fig. 11. From Fig. 11, position of a point A is $(\sin\theta, 1, \cos\theta)$, and point B is $(0, \sin\alpha, \cos\alpha)$. By the constraint that length of $\overline{AB}$ should be 1, θ and α should satisfy Eq. (1). The length from origin to point B is set as 1, because this analysis is just for finding constraint between θ and α.

$$\cos\theta\cos\alpha + \sin\alpha = 1 \quad (1)$$

In the next step, the whole magic-ball structure is plotted as linkages and joints model in Fig. 12 and 13. Figure 12 shows kinematic model of the wheel structure in y-z plane. R means a radius of the wheel, and L_{spring} means the half length of the wheel. 2s means the length of basic components and r means radius of the spoke plate. We assume that the joint angle of point C is 90° for simplicity because adjacent folding angles which determine the joint angle of C remain almost unchanged in deformation. From Fig 12, half side length of the wheel, L_{spring} and radius of the wheel, R can be calculated as follows.

$$L_{spring} = s\cdot\sin\alpha + 2s\cdot\cos\beta - 0.5s\cdot\sin\beta \quad (2)$$

$$R = r + 2s\cdot\sin\beta + 0.5s\cdot\cos\beta \quad (3)$$

Figure 13 shows kinematic model of the wheel structure in x-z plane. From figure 13, small radius of the wheel, R' and length of SMA coil spring actuator can be calculated as follows.

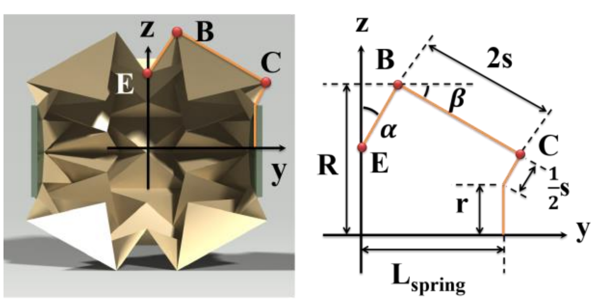

Figure 12. KINEMATIC ANALYSIS OF THE WHEEL IN y-z PLAIN.

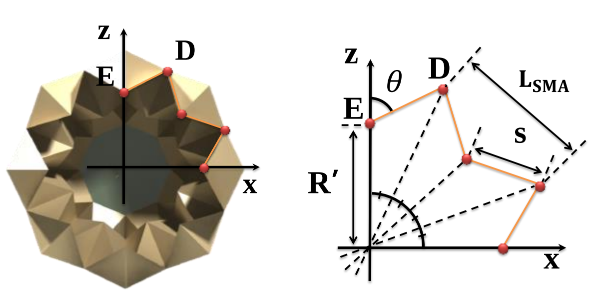

Figure 13. KINEMATIC ANALYSIS OF THE WHEEL IN x-z PLAIN.

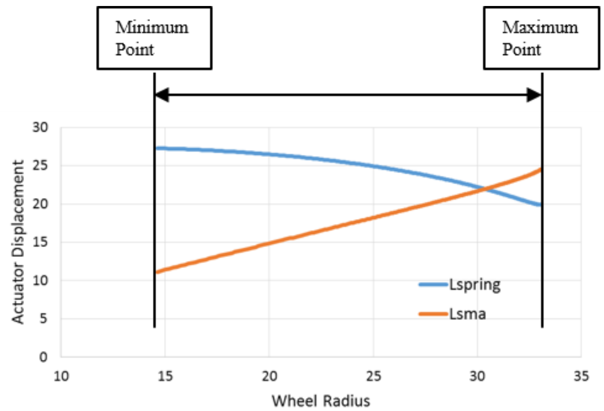

Figure 14. NUMERICAL CALCULATING RESULT OF RELATION BETWEEN THE WHEEL RADIUS .WITH THE ACTUATOR DISPLACEMENTS USING MATLAB

Table 1. VALUE OF THE VARIABLES IN BOUNDARY CONDITIONS.

	α	β	θ	L_{SMA}	L_{spring}	R
Undeformed State	60.7°	55.2°	70.5°	24.5	20.0	33.5
Deformed State	5.7°	0°	25.2°	11.1	27.3	14

Table 2. DECISION OF DISPLACEMENT FOR THE ACTUATORS

	Minimum Length	Maximum Length (mm)	Total Displacement
SMA Spring	11.1 mm	24.5 mm	13.4 mm
Passive Spring	40.0 mm	54.6 mm	14.6 mm

$$R' = s\cdot\frac{\sin(\theta-\frac{\pi}{8})}{\sin\frac{\pi}{8}} \quad (4)$$

$$R - R' = s\cdot\cos\alpha \quad (5)$$

$$L_{SMA} = 2s\cdot\sin\theta \quad (6)$$

From Eq. (3), (4) and (5), another constraint are obtained.

$$r + 2s\cdot\sin\beta + 0.5s\cdot\cos\beta \ - \ s\cdot\frac{\sin(\theta-\frac{\pi}{8})}{\sin\frac{\pi}{8}} = s\cdot\cos\alpha \quad (7)$$

In summary, there were two design constants, r and s, and three variables, α, β and θ, and two constraint Eq. (1) and (7). Because these equations are nonlinear and much coupled, it is hard to present explicit solution. Matlab, numerical computing tool, was used for analysis of the equations.

Figure 14 shows the result of calculation. The graph plot the relation between the wheel radius with the displacement of actuators. The r and s was set as 8-mm and 13-mm. Tab. 1 shows boundary conditions and Tab. 2 shows actuator conditions calculated from tab. 1. The boundary condition for undeformed state was decided by finding maximum value of R, and the boundary condition for deformed state was decided when β was 0° This data were used for design of the actuators.

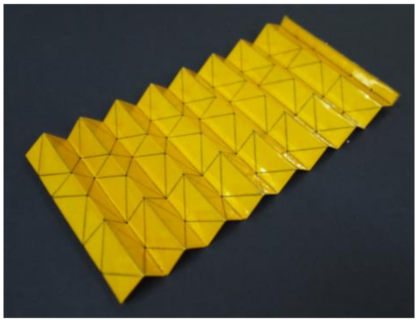

Figure 15. A PAPER COATED BY POLYIMIDE FILM. IT STILL HAS PROPERTY THAT EASY TO CARVING THE FOLD LINE.

FABRICATION

Wheel Fabrication

Material. In wheel fabrication, a paper with polyimide film (Kapton) was used. A paper is good material for carving a fold line and therefore, it has been a basic material for the art of origami. A fold line of a structure can be achieved by just folding a paper. However, a paper is weak in shear stress, and it is easy to be torn by small force. Although the paper is cheap and common material, it is dangerous to use the paper as a wheel material. For reinforcing the property of the paper, polyimide film which has an adhesive layer on one side was used. Figure 15 shows the paper with polyimide film. It still has the property of easily being folded, and shows much higher resistance in shear stress.

Method. One of the important issues in origami structure fabrication is to determine how to assign the stiffness difference between facets and fold lines. The stiffness of the fold line of the wheel structure impedes the wheel deformation and therefore,

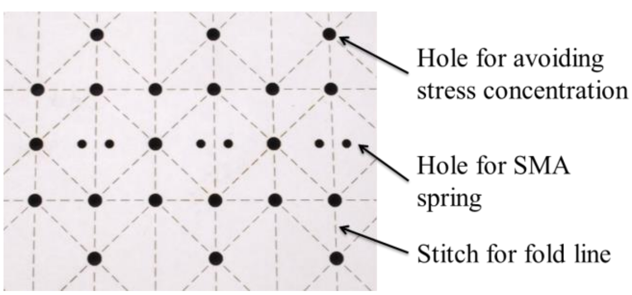

Figure 16. PATTERN FOR LOWERING DEFORMATION STIFFNESS [14].

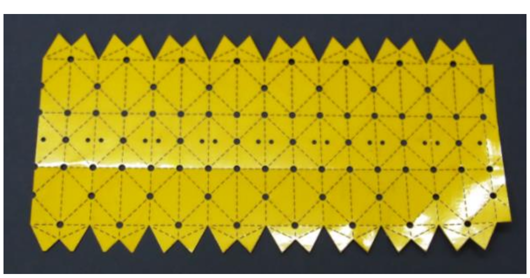

Figure 17. FABRICATION RESULT OF THE WHEEL PATTERN.

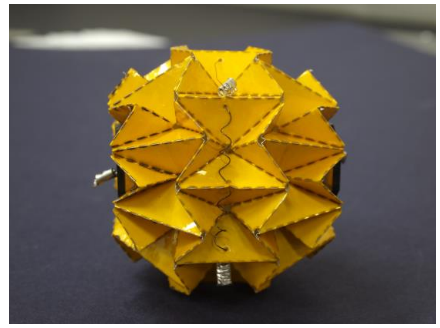

Figure 18. ASSEMBLY RESULT OF THE WHEEL STRUCTURE.

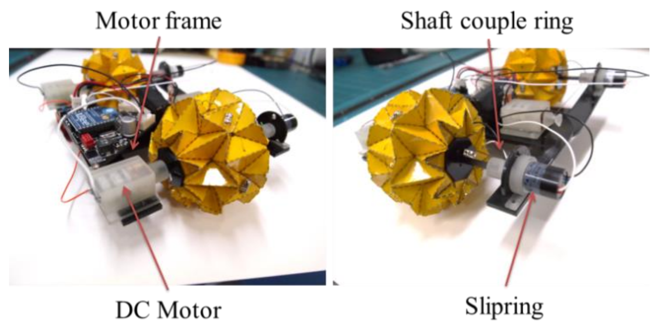

Figure 19. ASSEMBLY RESULT OF THE ROBOT.

some methods for weakening the stiffness of the fold line are needed. In this robot, two methods suggested by Onal *et al.* was used [14]. First one is to punch holes on vertex points where high stress is concentrated. Second one is to cut the fold line in stitch shape. Laser machining by universal laser cutter (ULS inc. M-300) was used for patterning of the material as in Fig. 16. Fabrication results of the wheel are in Fig. 17 and 18.

Other Components

The whole structure of the robot is in Fig. 19. The body of the robot was made by acrylic plate machined by laser cutter and other connecting parts were made by rapid prototyping machine (ProJet HD3000). Two lithium-polymer batteries (7.4 V, 700 mA each) were used; one is for control circuit and motor and the other is for SMA heating. The controller of the robot was Atmel's Atmega128, and wireless communication was achieved by Zigbee (Maxstream XB24). The electric motor (DnJ RA-12WGM) was installed for normal driving. The current for SMA was driven by MOSFET (On semiconductor NTR4501N) and the slipring (Pan-link Tech. PSR-M6) was used for current transmission to the wheel. For deformation of the wheel, the SMA coil spring actuator made by Dyn. Flexinol wire with dia. 10 mil was used. More detailed design and optimization works about SMA actuator will be conducted in future work.

EXPERIMENTAL RESULT

Figure 20 and 21 show the results of the deformation of the wheel. The diameter of the wheel changes from 7-cm (in normal state) to 5.5-cm (in deformed state) which shows 21.5% of

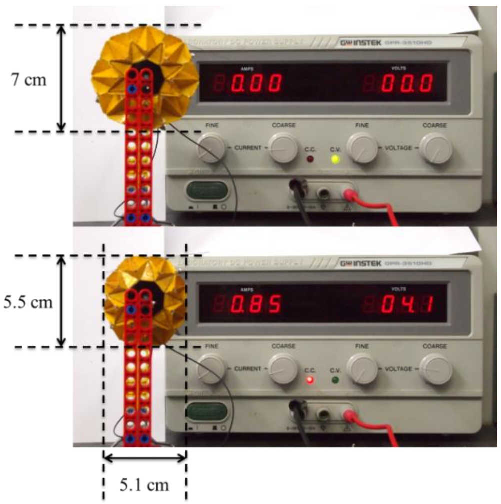

Figure 20. RESULT OF THE DEFORMATION TEST. THE WHEEL CAN DEFORM FROM ABOUT 7-cm DIAMETER TO 5.5-cm DIAMETER

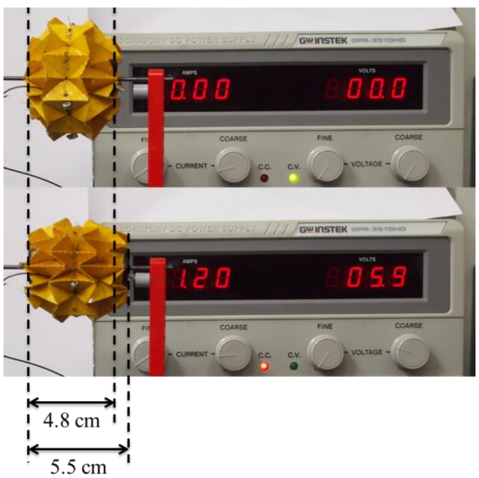

Figure 21. RESULT OF THE DEFORMATION TEST. THE SIDE LENGTH OF THE WHEEL CHANGE FROM 4.8-cm TO 5.5-cm

decreases. Because of the stiffness of the structure, friction of the shaft and not enough force of the SMA spring, the deformed diameter of the wheel is much bigger than the theoretical value (28-mm). And also, because of the position of the actuator, the wheel has unsymmetrical shape. This will be improved by using more optimized actuator in future work.

Figure 22 shows snap shots of the video clip which show the robot passing through a small slit by deforming of the wheel. The diameter of the wheel is 7-cm in normal state but by deforming of the wheel, the robot can pass through the 5.5-cm slit. Figure 23 shows steering ability of the robot. By using wire, spring and geared motor, the robot can steer in both directions although the wheel has a friction.

CONCLUSION

In this paper, we present the deformable wheeled robot using the particularly designed magic-ball structure. By using this special structure, we can achieve a wheel with mechanical functionalities like other mechanism.

In practical design of the wheel, a novel spoke design was adopted and for deformation of the wheel, certain actuation method using SMA coil spring was also suggested. Moreover, by constructing kinematic model of the structure, it was possible to predict the movement and performance of the structure. In fabrication of the wheel, a paper with polyimide film was used which is easy to make fold line and also has high shear resistance. As a result, the robot can move forward, backward, to the left and to the right. And by deforming the wheel, the robot can pass through 5.5-cm slit even the wheel of the robot has 7-cm diameter in normal state.

In future works, we will try to build a more precise model of the wheel structure. Actually, total displacement of passive

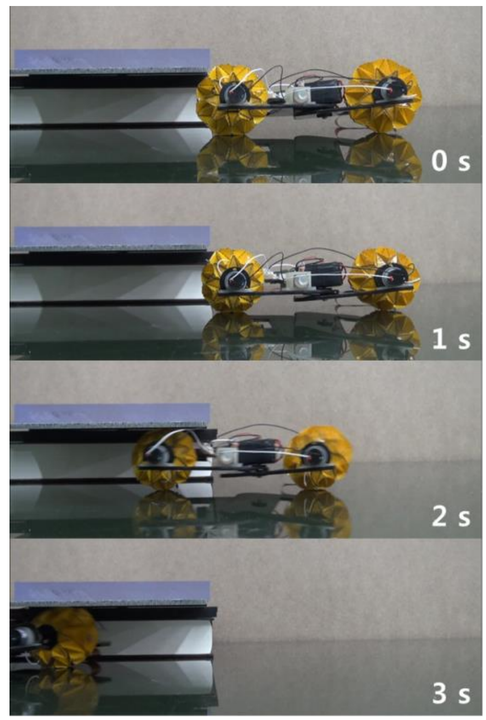

Figure 22. THE ROBOT CAN PASS THROUGH 5.5-cm SLIT USING DEFORMATION OF THE WHEEL.

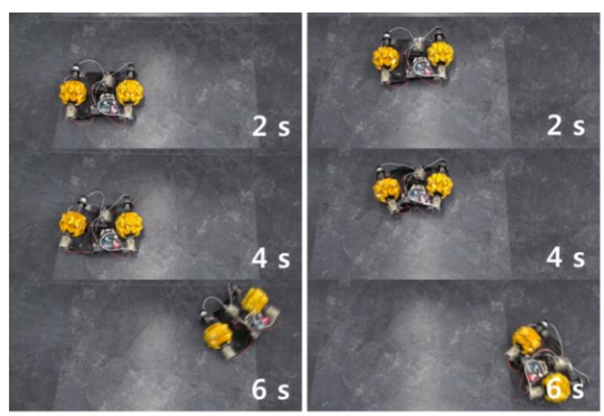

Figure 23. THE ROBOT CAN STEER IN BOTH DIRECTIONS ALTHOUGH THE WHEEL HAS A FRICTION.

spring is about 7-mm in actual wheel which is much larger than theoretical analysis and this is caused by punching holes for avoiding stress concentration and curvature of facet. We will analyze how this condition affects the condition for actuation. Also, we will build a kinetic model of the structure. In the assumption that this structure has a symmetrical shape, it is possible to calculate stiffness of the whole structure by treating each fold line as a torsional spring. Adding a model of SMA coil spring actuator and passive spring to this model, it can be possible to more precisely predict the movement of the robot and to design more efficient structure for actuation. And also, actuation method or actuator attachment point could be changed for more efficient actuation. Although we just analyzed the structure in this paper, we will be able to determine design parameters of the structure in the next step to obtain an improved version with better performance.

ACKNOWLEDGMENTS

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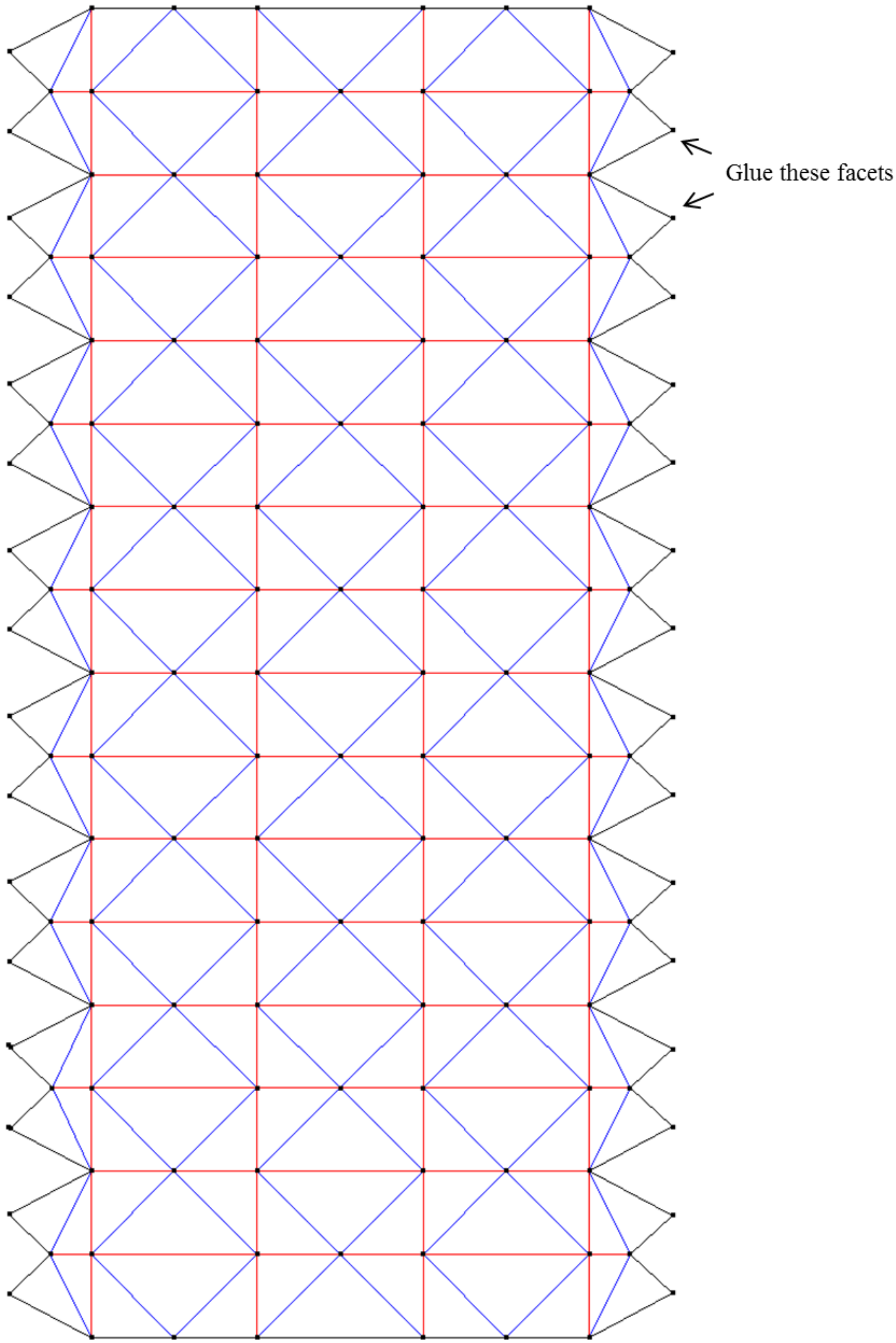
ANNEX A

ORIGAMI WHEEL PATTERN (DESIGNED BY 'ORIPA')



ANNEX B

ORIGAMI WHEEL PATTERN WITH STITCH AND HOLES