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Solar energy-actuated back and forth optical mechanism

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A self-active back and forth motion mechanism for optical systems was designed and realized without electrical power consumption. The system utilized the beam converging feature and thermal heating performance of lenses in combination with the thermal-based phase-changing feature of a shape memory alloy (SMA) actuator. Prototype 1 was designed and fabricated with a fixed lens group and a movable lens group, and its feasibility was confirmed through experiments. An optimized focusing pattern suitable for the SMA actuator was realized by employing a cylindrical Fresnel lens, and prototype 2 was built using a simplified fabrication method. We believe that our design is economical and environment friendly. A few potential applications can be optical/mechanical switches for solar energy panels, control units for outdoor equipment, and solar power chargers.

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1. INTRODUCTION

Motors, such as stepping motors, voice coil motors or servo motors, are commonly employed in optics systems to realize lens focusing or zooming [1,2]. These motors are typically run on electrical power. Therefore, if electrical power supply stops, all optical systems will stop working. We propose the design of a lens actuator mechanism that does not require electrical power.

The operation of lenses is based on the transmission and/or bending of light beams. The temperature at a focusing spot changes dynamically according to focus or defocus situations. In sunlight, a high temperature is generated under a focus situation and temperature decreases under a defocus situation. We aim to utilize this dynamic thermal change to design a mechanical actuator.

A shape memory alloy (SMA) is a smart material, which is also referred to as an artificial muscle [3–7]. It is a special alloy material that "remembers" its original shape and returns to its predeformed shape after deformation when heated over its transition temperature, as shown in Fig. 1. An SMA consists of two stable phases, i.e., austenite for high-temperature conditions and martensite for low-temperature conditions. The key effects of SMAs associated with phase transformation are pseudo-elasticity and the shape memory effect. As this effect is a temperature-induced phase transformation [8–11], there is no electrical power consumption. Furthermore, as lens movement leads to dynamic thermal variation, an SMA is one of the most suitable candidates for our actuator system.

One design forever use/move is our original thought. This design utilizes the light converging performance and thermal heating performance of lenses and combines them with the thermal-based phase-changing feature of SMAs. The design meets our original goal. Two prototypes were built. Prototype 1 was designed and fabricated with a fixed lens group and a movable lens group, and its feasibility was confirmed via experiments. An optimized focusing pattern suitable for an SMA actuator was realized by employing a cylindrical Fresnel lens, and prototype 2 was built using a simplified fabrication technique. We believe that the design is useful, and in this study, we perform the first step of the experimental approach to prove the feasibility of the design. A few potential applications are expected to be optical/mechanical switches for solar energy panels, control units for outdoor equipment, and solar power chargers.

2. DESIGN PRINCIPLE

A. Shape Memory Alloy and Phase Movement

An SMA was employed in our design because it could be reshaped when heated over its transition temperature. A spring-shaped SMA actuator was utilized, and a normal spring was used to provide balanced force. The force of the SMA spring varied according to its temperature owing to the change in the spring constant. The length of the normal spring

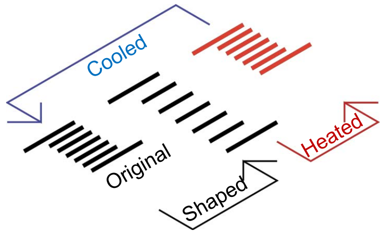


Fig. 1. Shape transition performance according to the temperature of shape memory alloy.

changed when the balance position of the joint was changed. The direction of phase movement was determined by which spring provided the domain force in that period.

B. Premeasurement of Spring Constant Coefficient of the Shape Memory Alloy

The properties of springs differ based on the types of springs [10,11]. Hence, a pre-experiment was conducted to measure the spring constant coefficient of the Ni–Ti-based SMA spring candidate (Kenis, 1-114-0195). According to technical data, the length of the SMA spring was 20 mm, its diameter was 10 mm, and wire diameter was 1 mm. The transformation temperature was 50°C. One side of the SMA spring was fixed on a wall, and its other side was connected and fixed to a force gauge (AANDD, AD-4932A-50N). The force gauge was fixed on a table. The SMA spring contained 20 coils, and the diameter of each coil was 1.0 mm. The shortest length of the SMA spring was 20.0 mm, and it was prestretched to a length of 30 mm. A heater (Hitachi, HD-N7700) was employed to heat the SMA spring, and a thermal camera (FLIR, C2) was set to monitor the temperature of the SMA spring. When the temperature was increased, the length of the SMA spring did not change. However, the force increased, which was measured by the force gauge. When the temperature increased up to 55°C, the heater was stopped and the SMA spring was naturally cooled down to 35°C. The variation in force with temperature was recorded. The spring constant coefficient was calculated based on the measured force data. The relationship between temperature and the spring constant coefficient (k-T) is plotted in Fig. 2. The red and blue curves show the trends of increase and decrease in temperature, respectively.

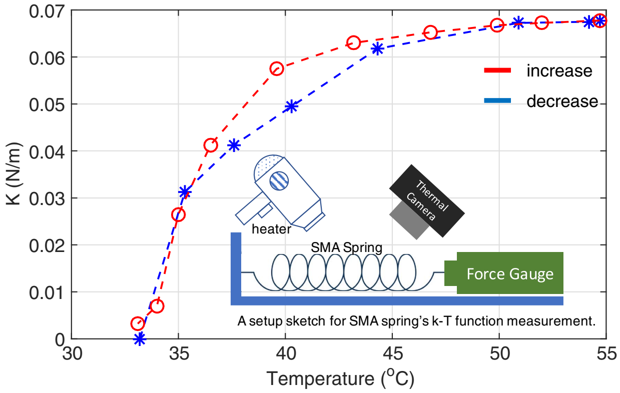


Fig. 2. k-T graph of SMA spring when it was prestretched to 30 mm.

C. System Architecture and Optical Design

The principle of the optical movement mechanism has already been shown in Fig. 3. Normal springs are used and set on one side of the movable lens plate, while the SMA spring is placed on the opposite side, so that a balance point of the normal spring force and SMA spring force is obtained. The position of the movable lens plate stops at this joint balance point. The balance point changes dynamically owing to change in the elastic coefficient of the SMA spring.

A flow chart of the phase shifting mechanism is shown in Fig. 4. The detailed operational flow is as follows: the first lens unit is employed to collect sunlight. The collected light reaches the second lens unit, which is the movement lens unit. As a result, a focus spot is formed on the SMA spring at the bottom of the system. The SMA spring is heated by the sunlight spot. When its temperature is over the transition temperature, the spring constant coefficient of the SMA spring increases and leads to shape deformation. The SMA spring shrinks, the standard spring becomes stretched, and the movable lens unit is moved downward. The SMA force becomes the domain force, and the static balance between the SMA spring and standard spring is modified. Thus, the system changes from phase one to phase two. In phase two, sunlight is defocused on the SMA spring owing to the change in the position of the second lens unit. Then, the SMA spring changes to the cooling mode.

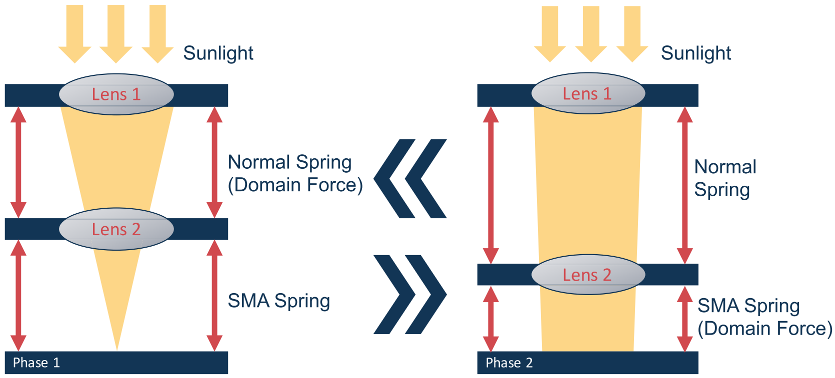


Fig. 3. Phase movement. Direction of the phase movement was determined by which spring provided the domain force in that period.

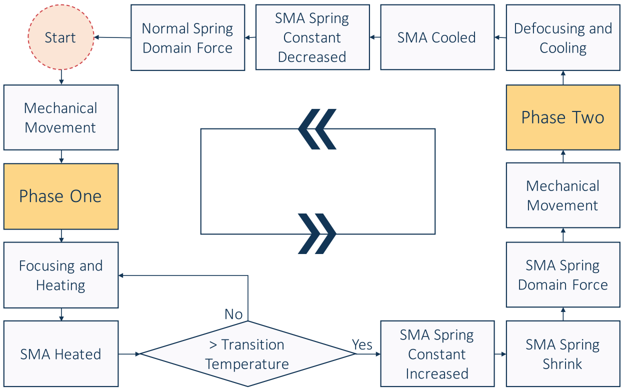


Fig. 4. Flow chart of phase movement.

The spring constant coefficient decreases, and the normal spring force becomes the domain force. The balance point is recalculated; this results in mechanical movement.

3. EXPERIMENT

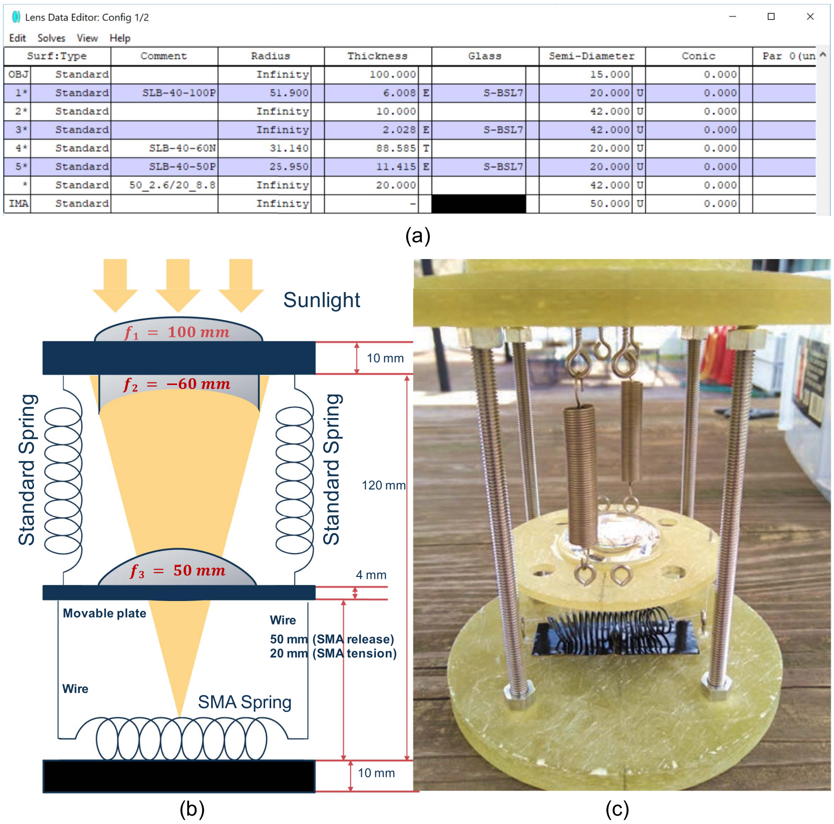
A. Prototype 1

A prototype was built, and it is shown in Fig. 5(c). Two standard springs (Tohatsu-Spring, JB-230) were hung vertically on the upper side, and an SMA spring (Kenis, 1-114-0195) was placed horizontally on the lower side. Eye lag screws were fixed on the bottom plate. The ends of the SMA spring were fixed with wires, passed through eye lag screws, and connected to the lower side of the plate. Three lenses, i.e., SLB-40-100P, SLB-40-60N, and SLB-40-50-P from Sigma-koki, were set according to the optical simulation by Zemax.

The experiment was conducted in Tokyo, Japan, where sunlight was not incident vertically downward. The system was placed at a tilted position to ensure that sunlight was incident vertically, as shown in Fig. 6(a). It was confirmed that the SMA spring changed from the release phase [Fig. 6(b)] to the tension phase [Fig. 6(c)]. The transformation from phase one (release phase) to phase two (tension phase) was completed in approximately 25 s. The heating spot was circular, but the SMA spring was cylindrical. The thermal transmission from one spot to the entire spring was the main reason for the high time consumption. The movable lens unit (lens 3) was moved approximately 10.0 mm downward. The SMA spring transformation from phase two to phase one was completed in approximately 9 min because the cooling procedure was slow owing to the high surrounding temperature. A cylindrical Fresnel lens was employed to improve the performance of the system and simplify the fabrication.

B. Prototype 2

Conventional lenses are circular; thus, focus spots are also circular. However, the SMA spring was cylindrical in shape, and hence, a normal circular lens could only illuminate one part of the SMA spring, as shown in Fig. 7(a). The response time increased owing to slow thermal transmission. A cylindrical lens focuses light into a line-shaped pattern instead of a point spot. The line-shaped focus pattern provides better focusing



	Surf:Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(un
OBJ	Standard		Infinity	100.000		15.000	0.000	
1*	Standard	SLB-40-100P	51.900	6.008 E	S-BSL7	20.000 U	0.000	
2*	Standard		Infinity	10.000		42.000 U	0.000	
3*	Standard		Infinity	2.028 E	S-BSL7	42.000 U	0.000	
4*	Standard	SLB-40-60N	31.140	88.585 T		20.000 U	0.000	
5*	Standard	SLB-40-50P	25.950	11.415 E	S-BSL7	20.000 U	0.000	
*	Standard	50_2.6/20_8.8	Infinity	20.000		42.000 U	0.000	
IMA	Standard		Infinity	-		50.000 U	0.000	

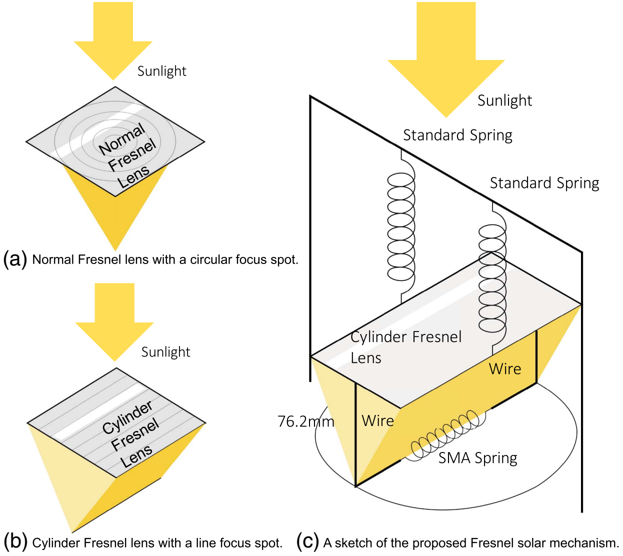
(a)

(b) (c)

Fig. 5. (a) Screenshot of the optical simulation. (b) Sketch and dimensions of system. (c) Photograph of prototype 1 of the system.


(a) (b) (c)

Fig. 6. (a) System placed at a tilted position toward sunlight. (b) Transformation of the SMA spring from the release phase to (c) the tension phase.



(a) Normal Fresnel lens with a circular focus spot.
(b) Cylinder Fresnel lens with a line focus spot.
(c) A sketch of the proposed Fresnel solar mechanism.

Fig. 7. Compression of the focus shape between (a) normal Fresnel lens and (b) cylindrical Fresnel lens. (c) Sketch of the proposed Fresnel solar mechanism.


(a) (b)

Fig. 8. (a) Prototype 2, where a cylindrical Fresnel lens was employed and the system was simplified. (b) The proposed Fresnel solar mechanism worked under sunlight, and a line focusing pattern was confirmed.

on the entire body of the SMA spring, as shown in Fig. 7(b). To simplify the fabrication procedure, the optical system consisting of one fixed lens and one movable lens was changed to consist of only one movable cylindrical lens because the cylindrical lens could provide more effective focusing power. A cylindrical Fresnel lens was employed to minimize the volume of the prototype and simplify the system. A sketch of the proposed Fresnel solar mechanism is shown in Fig. 7(c).

A prototype was built according to the sketch image. The cylindrical Fresnel lens (83-X-102-X-76, Edmund) was set at a distance of 76.2 mm (back focal length) from the SMA spring so that the focal pattern would be on the SMA spring in the release state. Similar to prototype 1, two standard springs (Tohatsu-Spring, JB-230) were hung vertically on the upper side, and an SMA spring (Kenis, 1-114-0195) was placed horizontally on the lower side. The ends of the SMA spring were fixed with wires, passed through eye lag screws, and connected to the cylindrical Fresnel lens. A photograph of the prototype is shown in Fig. 8(a), and a line focus pattern could be confirmed, as shown in Fig. 8(b). With the more efficient heating of the Fresnel lens, the response time of the transformation from phase one to phase two was 5.0 s.

When the SMA spring was shrunk, the cylindrical Fresnel lens element was pulled down. The standard spring on the opposite side of the lens maintained the force balance, and hence, it was stretched. Thus, the cylindrical Fresnel lens moved downward by a distance of 10.0 mm. In this prototype, fabrication was simplified and heating efficiency was improved. However, as only one lens was employed in this system, the heating procedure was evidently improved but the cooling mode was not efficient. Improvement ideas in this aspect are discussed in the next section.

4. DISCUSSION AND CONCLUSION

An important aspect of this (and future) work is to achieve optical movement without electricity consumption. To address the above challenge, a system was designed based on lenses, an SMA spring, and solar energy. The optical design was constructed to ensure that sunlight could be collected and utilized to generate heat in the SMA spring to actuate the motion of the system.

The optical simulation by Zemax was employed, and prototype 1 was fabricated with a fixed lens group and a movable lens group. The SMA spring was controllable when sunlight was collected and the SMA spring was heated. The designed system met the research goal. However, heating efficiency was not good owing to the small focus spot formed using the circular lens.

A line-shaped focusing pattern was determined to be suitable for the shape of the SMA spring and to enhance phase transformation performance. Thus, a cylindrical lens was employed instead of the circular lens. To simplify the fabrication procedure, a cylindrical Fresnel lens was employed to build prototype 2. Experimental results confirmed that prototype 2 exhibited evident improvement in the transformation from phase one to phase two.

The next challenge in this work is to improve cooling performance. In this regard, one idea is to develop a mechanical shutter associated with the shrinking movement of the SMA spring, so that sunlight will be blocked by the shutter when the system is in phase two. Thus, the SMA spring would not be illuminated by sunlight and cooling performance would be improved.

Another challenge is that the angle of the illumination of sunlight changes while the sun moves. Hence, a solar tracker is required to ensure the device can follow the movement of the sun and is directly illuminated by sunlight. However, most solar tracking devices require electricity, and this is contrary to our original thought. Therefore, a nonelectric solar tracker would be developed.

One design forever use/move is our original thought. This work utilizes the light collection performance and thermal heating performance of lenses and combines them with the thermal-based phase-changing feature of the SMA spring. Experimental results proved that the mechanical movement of the above optical system was realized without the consumption of electrical power, and thus, we believe that the design is useful. The proposed system can find potential applications in optical/mechanical switches for solar energy panels, control units for outdoor equipment, solar power chargers, etc.

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