An SMA-actuated, Compact, Compliant Ring-actuator with Uniform Deformation

Puneet Singh and G. K. Ananthasuresh

Abstract

This paper describes the design, prototyping, and testing of a single-piece compliant ring-actuator that can deform radially to grasp and release objects of regular polygonal shapes. The ring-actuator comprises a compliant mechanism that converts circumferential motion to radial motion of its multiple contact pads, two shape-memory-alloy (SMA) wires that provide circumferential actuation, and insulating roller guides. A new feature of this actuator is that its contact pads move in unison because of the uniform deformation of the underlying compliant mechanism. The outer diameter of the ring-actuator is 90 mm while the diameter of the circle made by the inner contact pads is 59 mm. Thus, it has a radial span of 15.5 mm. The weight of the ring-actuator is 52 g. With 2% strain in the SMA wires, the pads can move radially outwards by 1.5 mm. This means that there is a displacement of about 10% of the radial span. The experimental prototype had about 1.2 mm radial displacement for an induced strain of 1.75%. One of the uses of this ring-actuator is in grasping an object externally and thereby enabling an external pipe-crawling device with inchworm motion.

Keywords: compliant mechanism, shape memory alloy, deployable actuator, pipe crawler, robotic system

1 Introduction

In recent years, radially deployable mechanisms have gained popularity in various forms: from toys to complex space-structures [1-6]. Most of deployable mechanisms are kinematically over-constrained and possess many rigid links and joints. They are suitable in applications where there is no space constraint and a long range of motion is desired. When the range of motion is short, compliant designs that are free from kinematic joints are preferred. One such compliant deployable mechanism (see Fig. (1)) was developed based on a circumferentially actuated radially deployable linkage [6]. It was used in an external pipe-crawling robot [7, 8]. It imitated inchworm motion with the help of two expandable rings connected by linear actuators and springs. In inchworm motion, one of the rings translates forward while the other is clamped. When the translated ring is clamped, the first ring advances. Polypropylene

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prototype of one of the rings is shown in Figs. (1a-b) with deformed (i.e., clamping) and undeformed (i.e., expanded and hence non-clamping) configurations. It is a two-layered structure in which specially designed compliant segments protrude radially inwards from the rings. The two layers, which are mirror images of each other about the axis perpendicular to the rings, are connected to each other at the innermost points where contact pads are located. Figures (1a-b) show fasteners but the ring in the pipe-crawling robot was a monolithic two-layered structure [8]. When the rings are rotated relative to each other, the compliant segments retract radially outwards as can be seen in Fig. (1b). this releases the grasp on the object.

The ring actuator, whose working prototype made using spring steel was demonstrated in our previous work [8], had some problems: (i) over-heating of the device due to repeated SMA actuation, (ii) lack of proper electrical isolation, and most importantly, (iii) non-uniform movement of its three compliant segments. This paper focuses on addressing these problems and demonstrates an improved prototype of the ring-actuator.

Figure 1: Circumferentially-actuated radially deployable compliant mechanism prototype (a) deformed and grasping a circular object (b) undeformed with the release of the grasp.

2 SMA-actuated Radially Deployable Ring-assembly

Radially deployable compliant mechanism converts circumferential motion to radial motion. Figure (2) shows the geometric model of the compact ring-actuator. Its two identical rings with four pairs of compliant segments each attached at the contact pads can be seen in the figure. Electrically insulating rollers are provided to guide two halves of the SMA wire. Earlier designs of [7, 8] had used a single wire to actuate and effect the relative motion of the two rings. The ends of the two SMA wires are capped with plastic clips after crimping. It can be noticed in Fig. (2) That the ring-actuator is compact in the radial direction beyond a circular object on which it is mounted. Its annular span in the radial direction is only 15.5 mm while its overall radius is 90 mm.

The SMA wire that we used needs to be stretched up to 2% strain before assembling onto the device because it was trained to recover a maximum strain of 2% for unlimited number of cycles. When the SMA wire is electro-thermally heated by passage of current, it heats up and shrinks as it transforms to its martensite state from the austenite state. This causes the relative circumferential motion of the rings. Compliant segments transform this to amplified radial motion at the contact pads. This releases the grip on the circular object. Upon turning off the electric current, the wires cool and reach the martensite state again. Then, the restoring force of the compliant segments pulls the wires back to their stressed states. This cycle repeats as many times as needed provided the original state is restored in terms of stress in the SMA wires and temperature conditions.

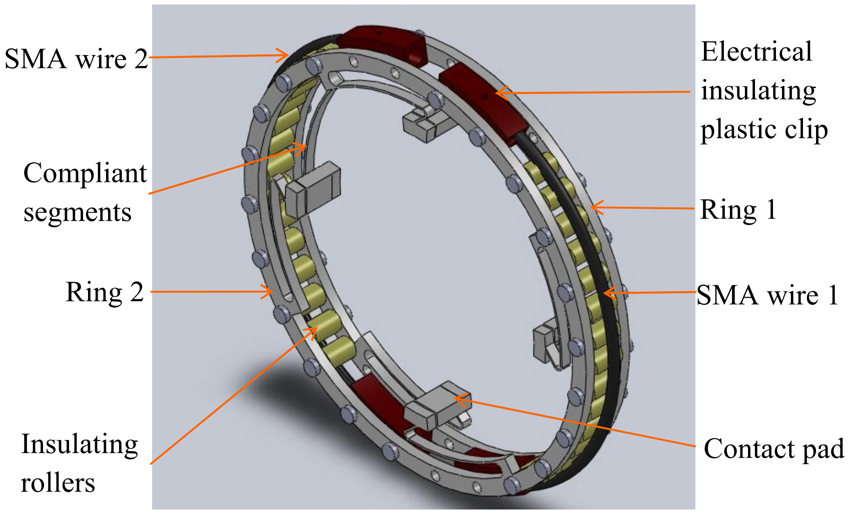

Figure 2: Geometric model of the ring-actuator.

We used 1 mm diameter Ni-Ti-Cu Shape memory alloy wires. From the manufacturers, it is known that the wire can exert a stress of about 100 MPa, which for a 1 mm diameter wire translates to about 78 N force. The length of the wire and the pre-strain in it had to be chosen carefully to exert force and displacement that match those of the compliant segments. Only then, repeatable operation is possible. In other words, the stiffness of the SMA wire and the compliant segments should match. Before doing this, it was imperative that the SMA wires be properly characterized.

The experimental setup for characterizing the SMA wires is shown in Fig. (3). the wire was pre-stretched by about 1.75%. As the wire was heated, there was deformation in the SMA wire. To see the deformation in the wire against different applied weights, we applied weights from 1 to 8 kg. With 8 kg weight, and with other weights, the deformation was 4 mm indicating that the wire is able to contract against a force of as much as 78 N. To calculate the stiffness in the martensite phase, we took the 226 mm long SMA wire and fixed it at one end while the other end was attached to a 8 kg weight. The SMA wire deformed by 1 mm due to the 8 kg weight. So, the stiffness of SMA wire in the martensite phase is (8×98.1×c/s area) 78.48 kN/m. To calculate the stiffness in the 'cooling phase' (during which material transitions from the austenite to the martensite phase), we took 230 mm (pre-stretched by 4 mm) long wire and fixed its one end in a bench-vice and applied 8 kg weight at the other end. With a 2 V power supply, the ensuing current heats up the wire and transforms the material to the austenite phase changing its length to 226 mm. Then, the power supply was turned off. As a result, austenite phase starts to transform into martensite phase. Due to weight, the SMA wire again deformed in the cooling phase up to 229 mm. So, the SMA wire deformed by only 3 mm in the cooling phase in 2 min. We repeated this experiment five times and found stiffness in the cooling phase to be 26.16 kN/m.

To make the repetitive motion possible, the stiffness of the compliant ring should be greater than the stiffness of the SMA wire in the cooling phase. Only then the compliant ring will stretch the SMA wire back to the stressed state. The stiffness of the compliant ring was calculated to be 73.11 kN/m by finite element simulation. This stiffness value is more than the stiffness of the SMA wire in the cooling phase. So, it ensures that repeated cyclical motion is possible.

Figure 3: Experimental setup for calculating the stiffness of the SMA wire in martensite and cooling phases. (a) Power supply (b) Bench Vice (c) Ruler (d) SMA wire (e) Weight

3 Modified Design and Finite Element Modeling

3.1 Uniform deformation

In the previous design [8], we had used a single shape memory alloy wire that was put along the circumference of the rings. The force on the compliant ring was not uniform when a single wire was used. This is because the force distribution was not uniform and hence caused misalignment (due to the extra degree of freedom) between the two rings as shown in figure 4(a). Hence, the four pads moved unequally with a single wire. As a result, one clamping pad moves in the inward direction while the rest of the three move in the outward direction as shown in Fig. 4(a). To solve this problem, we now use two SMA wires instead of one. The two SMA wires were put in such a way that both SMA wires apply the force uniformly on the ring and avoid extra degree of freedom. Its simulation is shown in Fig. 4(b) in which it can be seen that all clamping pads move equally in the outward direction by 1.5 mm. ABAQUS finite element simulation was done for this purpose. In ABAQUS simulation, we assumed that the lower ring is fixed and the force was applied on the upper ring as shown in Fig. 4(a-b). Tetrahedral elements with quadratic interpolation were used to mesh the mechanism.

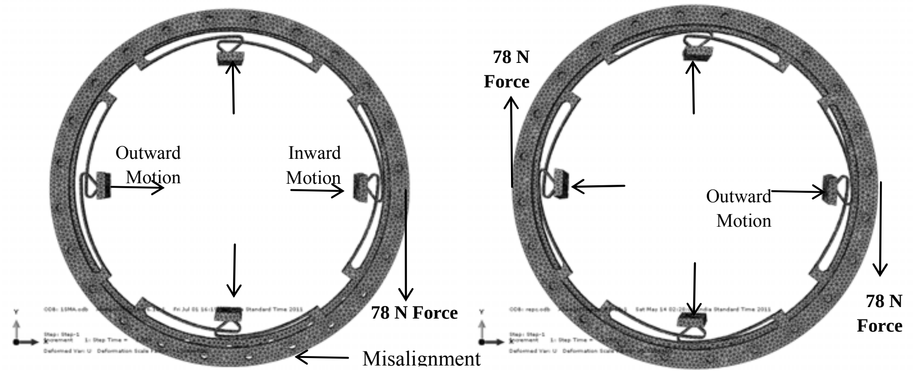

Figure 4: Deformation in the ring-actuator (a) with a single SMA wire (b) with two SMA wires. Unequal movement of pads is seen in (a), which is not the case in (b).

3.2 Griping and actuation forces

Since the outer diameter of the object on which the ring actuator is mounted is larger than the diameter of the circle passing through the four contact pads, there will be a force on the object due to 'interference fit' type situation. Therefore, the ring-actuator needs to be actuated and then put around the object. The resulting gripping force was determined to be 1.8 N per clamping pad. This was done by giving prescribed displacement to the pads in ABAQUS simulation and finding the reaction force. Similarly, the tangential force required to move the pads radially outwards was calculated using ABAQUS (see Fig. (5)). This force was found to be 17.1 N per compliant segment. Since there are four compliant segments, four times this force (i.e., 68.4 N) should not exceed the force that can arise from the SMA wires. This was ensured because SMA wire can apply as much as 78 N in the hot austenite state and needs only 52 N to stretch it by 2 mm in the cooled martensite state. Therefore, the compliant segments can stress the SMA wires in the martensite state and be actuated in the austenite state.

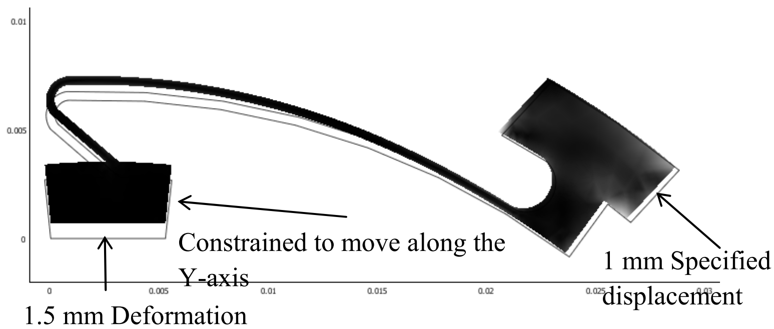

Figure 5: Deformation of a compliant segment.

3.3 Electrical insulation and roller guides

Spring-steel was used to make the ring-actuator shown in Fig. (2). this was because the restoring force to bring the SMA wires had to be sufficiently large (which is not possible with a plastic material unless the size is large) and to have good elastic behavior. Since spring-steel in an electrical conductor, it warrants proper electrical insulation between SMA wire and the rings. For this, several acrylic roller guides are used. Rolling guides solve two problems: electrical insulation and guiding the wire with little friction. Earlier designs did not have the guides and hence the wire had assumed a polygonal shape, which also led to unintended non-uniform deformation. Figure (6) shows a close-up view of the fabricated ring-actuator.

Figure 6: Electrical insulation of the actuator using acrylic roller guides shown with a close-up view of the fabricated ring-actuator.

3.4 Thermal modeling

It is important to understand the thermal behaviour of the SMA wire and the entire ring-actuator: (i) to make sure that the ring cools to room-temperature within reasonable time after one cycle of operation, and (ii) to ensure that all of SMA wire heats to 70º C transition temperature with 2 V. For (i), we performed an experiment on the ring-actuator and SMA wire and measured the temperatures. We used K-type thermocouples to measure the temperature shown in Fig. 7(a). The dotted line in the graph shows the temperature of the SMA wire while the other line shows the temperature of the spring-steel portion. It takes about 2 min to complete a cycle. Since the wires are exposed to outside in the current design, there is better provision for convective cooling as compared to previous designs of the actuator. We also did the 2D transient thermal modelling of SMA wire for (ii) using CMOSOL Multiphysics to calculate the temperature profile by applying 2 V electric potential. The temperature profile is shown in Fig. 7(b) at time 30 s. It can be seen that almost all of the wire reaches 40º C. This distribution continues to be so when the voltage is sustained for a longer time. Hence, all of the SMA wire uniformly undergoes phase transition. The material properties used in thermal modelling were: thermal conductivity = 18 W/ (m-K), density = 6800 Kg/m^3, and resistivity =7.6 $^{e-7}$ Ω-m for the SMA wire.

4 Prototyping

Compact compliant radially deployable actuator is assembled using two compliant rings as shows in Fig. 8. The compliant rings, as stated earlier, convert the circumferential motion into radial motion. First, we designed the compliant rings in SolidWorks software and the machine code was generated for wire-cut EDM using ELAPT software. The compliant rings were made out of spring steel (AISI 1080; EN 42J) cut on a wire-cut electro discharge machine (EDM). The spacers were also made up of spring steel on the same machine. Since the two rings are in two different parallel planes, they were soft-soldered with spacers at the clamping pads.

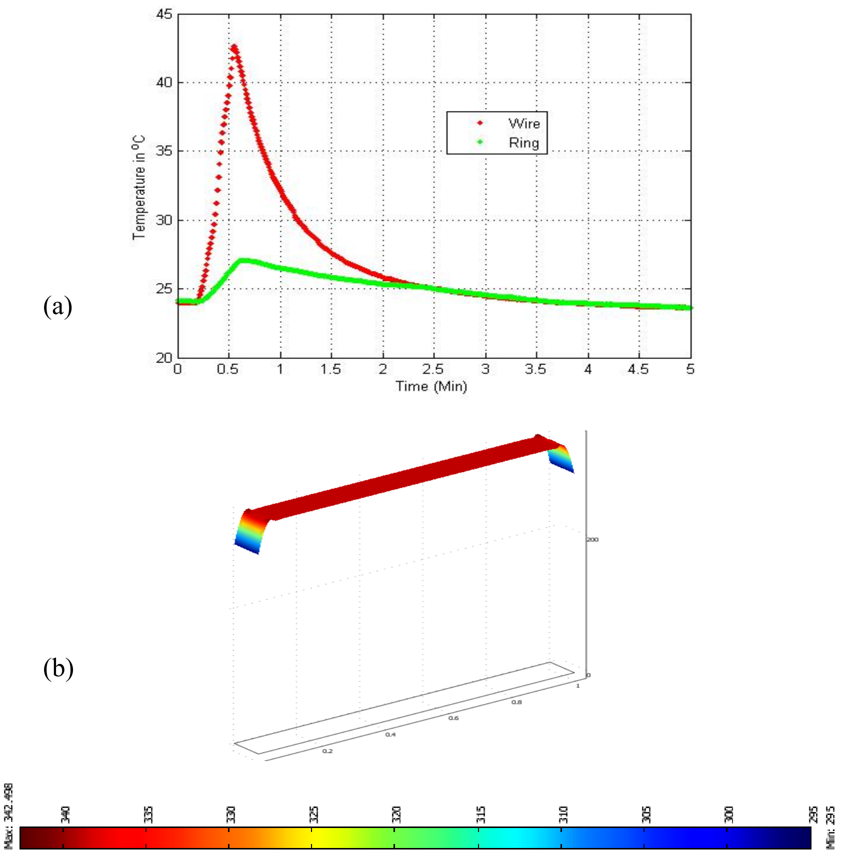

Figure 7(a) Temperature vs. time in the experiment, (b) temperature distribution of the SMA wire in its thermal modelling at time 30 s.

Two Ni-Ti-Cu shape memory alloy wires were connected in between the compliant rings with the help of a plastic clip and a brass crimpable tube. The SMA wires were connected in opposite directions. The acrylic rollers on which the SMA wire sits can be seen in Fig. 8 along with the other parts. Acrylic rollers were made on the CO_2 laser machine.

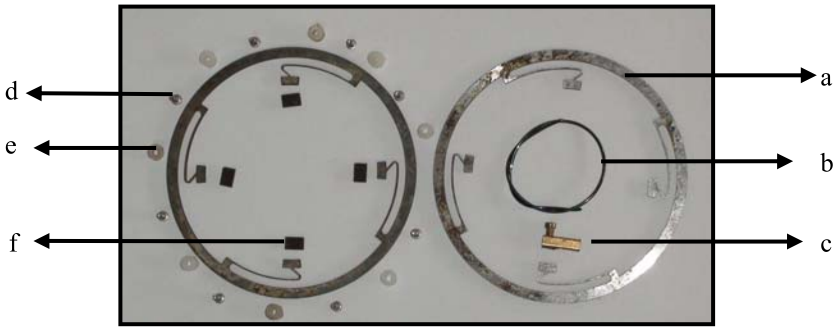

Figure 8: Parts of the ring-actuator. (a) Compliant ring (b) SMA-wire (c) Brass connecter (d) Screw (e) Acrylic rollers (f) Spacers.

5 Testing and Results

Figure 9 and 10 show the test setup. The setup shows the ring-actuator put on the pipe that is set vertically. Since the outer diameter of the pipe is larger than the diameter of the circle passing through the four clamping points, there is a gripping force of 1.8 N (per clamping pad) applied on the pipe. As can be seen in Fig. 8, it is adequate to hold the ring-actuator against its total weight equal to 52 g (= 0.51 N < (4×1.8) N). With 2 V potential, the ring loosens the grip on the pipe because of the radially outward movement of the contact pads. This experiment was done 20 times to calculate the deformation in the clamping pads without mounting it on the pipe. The maximum deformation on one clamping pad was 1.2 mm with a standard deviation of 0.02 mm. However, when we look at the movement of all the four pads, there is about 2.4 mm in the change in the diameters of the circles passing through the contact pads' outer edges in the unactuated and actuated configurations. Modeling showed that there should be 1.5 mm displacement of pads for 2 V. The discrepancy between the two may be due to inaccuracies in manufacturing and possibly non-uniform temperature distribution of the SMA wires. This will be investigated further to get the anticipated displacement (2.4 mm radial movement with 2 V potential within 150 s per cycle of actuation) of the ring-actuator.

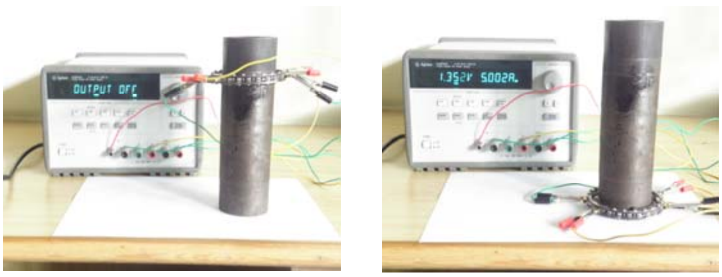

Figure 9: Experimentally setup for the actuator (a) with 0 V; the pipe is tightly gripped against gravity (b) with 1.35 V; the ring is released and fell onto the base of the ring.

Figure 10: Ring-actuator under testing: (a) before actuation (b) after actuation that resulted in 3 mm increase in the diameter of the circles passing though the clamping pads.

6 Closure

In this paper, we presented improvements made to a compact compliant radially deployable ring-actuator so that it has uniform movement of its contact pads. This is achieved by using two halves of an SMA wire so that the force distribution is uniform and heating is also uniform in the wires to give the same force for all the compliant segments of the ring-actuator. In this paper, we also solved the electrical insulation problem with the help of acrylic roller guides. These guides also give the rolling effect between the SMA wires and the rings so that the wires can move smoothly. Another problem was excessive heating of the SMA in the repeated operation of the actuator, which was leading to excessive time lag between successive gripping and release of the actuator. Since the wires are exposed to outside in the current design, there is better provision for convective cooling as compared to previous designs of the actuator. Integration of two ring-actuators with linear actuators between two ring-actuators is the next step of this work.

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