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An SMA-actuated, Compliant Mechanism-based Pipe-crawler

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ABSTRACT

The focus of this paper is the design and prototyping of a compact external pipe-crawling device that aids the inspection of pipes in hazardous environments and areas that are inaccessible to humans. The novel aspect of the design is a compliant mechanism that is actuated using Ni-Ti-Cu shape memory alloy (SMA) wire and strip. The device consists of two rings that are attached to each other along the longitudinal axis of the pipe by three pairs of circumferentially arranged U-shaped SMA and spring steel (AISI 1080) strips. Each ring consists of a compliant mechanism and housing. The compliant mechanism transforms the circumferential motion to radial motion at three points that are in contact with the pipe. The design of this compliant mechanism is derived from a radially deployable linkage. The SMA wire attached to the compliant mechanism and embedded within the housing with proper electrical isolation creates the circumferential motion for the compliant mechanism. When there is no actuation, the contact points of the compliant mechanisms of the two rings tightly hold the pipe. When an SMA wire of a ring is activated, that ring releases the grip on the pipe. At this time, the SMA strips are actuated to bring the rings closer together. After this, the first ring is de-activated to create the grip again. This is followed by releasing the grip on the second ring by the SMA wire activation. The spring steel strips, which are compressed during the SMA strip actuation, now extend back creating a displacement along the pipe. This cycle is repeated to create an inch-worm like clamp-and-push motion of the crawler. The device has been fabricated and tested. It also has a control circuit that activates the two SMA wires and the SMA strips cyclically. A unique feature of the design of the pipe-crawler is that the compliant mechanism provides the necessary kinematic function and it also serves as the bias spring for the SMA wires. A drawback of the device is that its crawling speed is low (about 1 mm/min), which is due to the time taken for heating and cooling the SMA wire and the strips.

Keywords: Compliant mechanism, shape memory alloy (SMA), pipe-crawling device.

1. INTRODUCTION

This paper is concerned with the development of a pipe-crawler. Many pipe-crawlers are reported in the literature. Most of them are internal pipe-crawlers; they crawl inside the pipe for inspection or to reach into an otherwise inaccessible area. The motion involved in such crawlers is one of the five types: wheel-based rolling, sliding with tracks or treads, walking with legs, clamp-and-push, and propulsion. Wheels and tracks (e.g., [1-4]) and walking with legs (e.g., [6,7]) require sensors and control to have the necessary gait, to prevent slipping, and to avoid obstacles. These are cumbersome and take up the entire space inside the pipe as they crawl. Propulsion-based systems are used in submarines and other underwater applications [4] and they are actually not crawlers. Clamp-and-push inch-worm like motion is less cumbersome and is less affected by irregularities inside the pipe in comparison with the other types. Different variations of internal pipe-crawlers based on clamp-and-push motion are proposed (e.g., [8, 9]). External pipe crawlers have received much less attention in the literature. A noteworthy external crawler [10] uses clamp-and-push motion. It uses a four-bar linkage to create clamping and release while a linear guide-rail creates the necessary motion along the pipe. This crawler is bulky and occupies a lot of space outside the pipe. Our crawling device is also an external device in the sense that it too rides on the outside of the pipe. And it uses the clamp-and-push motion. But there are two distinguishing features. First, we use a compact ring-type clamp based on a compliant mechanism. Second, we use shape memory alloy (SMA) actuation for the clamp and release as well as for linear motion. The SMA actuation and the compliant mechanism mutually benefit from each other: SMA provides the compact actuation to the mechanism while the compliant mechanism serves as the bias spring for SMA in cyclical operation.

The motivation for the compact external pipe-crawler is the need to move thickness-monitoring sensors along a pipe among a bundle of such pipes. Since each pipe is in a bundle, the space available outside the pipe is very limited. Typically, for a 50 mm diameter pipe, only 10 mm radial space is available around the pipe. This means that we have only annular space between 70 mm and 50 mm diameters (see figure 1). The clamping mechanism, the linear actuation, and the actuators must, therefore, fit within this space. This requirement is met by our crawler whose design is explained in Sections 2 and 3. Section 2 contains the description of the compliant mechanism while Section 3 contains the details of the actuation and the assembly of the entire device. Section 4 presents the prototype and its testing. Concluding remarks are in Section 5.

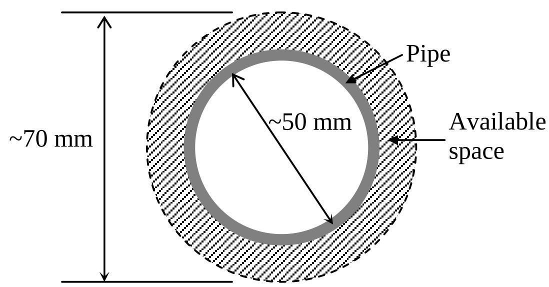


Figure 1. Spatial specifications of an external pipe-crawler. Only the hatched annular space is available for the crawler.

2. CIRCUMFEENTIAL COMPLIANT CLAMP

2.1 Clamp-and-push crawling concept

As shown in figure 2, the device consists of two circumferentially expandable/contractible rings labeled A and B. The two rings hold the pipe snugly when there is no actuation. A ring would release its grip upon actuation. The two rings are attached to each other by a set of translational springs and actuator group arranged circumferentially. In order to crawl to the right, ring B grips the pipe tightly and stays unactuated while ring A is actuated to release its grip. The linear actuator pushes ring A closer to ring B. In this process, the translational springs too get compressed. At this stage, actuation to ring A is stopped and thus making it grip the pipe again while ring B is released and translational actuator is also de-activated. Now ring B is pushed to the right because the compressed translational springs relax to their undeformed state. This constitutes one cycle and leads to a small movement to the right. By repeating this cycle, the device crawls over the pipe. By reversing the roles of rings A and B in a cycle, the crawling direction can be changed. This concept works for an internal crawler too but here we focus on only the external crawler. We present the kinematic design for the clamping mechanism next.

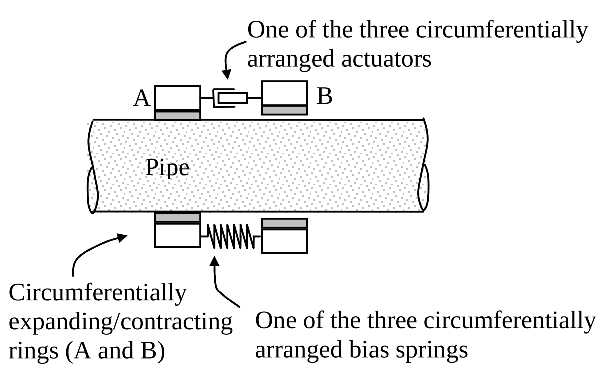


Figure 2. Schematic illustration of a clamp-and-push concept of a pipe-crawler.

2.2 Kinematic basis for the circumferential clamp

Radially deployable planar linkages have received considerable attention in recent years [11-14]. Hoberman's linkage is a popular toy [11] while more general types have found applications in deployable roof structures and other applications [12,13]. These linkages are over-constrained (i.e., they have negative degrees of freedom as per Grubler's formula [14]) but have special geometry that permits them to move in or out radially as shown in figures 3a-b. Such a device can be used to clamp around a pipe and release upon actuation. A new type of radially deployable linkage was derived from a general theory in [14]. In this type, circumferential actuation is given to achieve the radial deployment. This is illustrated in figures 4a-b. Both of them have many joints and parts and are not suitable for fitting into a narrow annular space shown in figure 1. So, we developed a compliant design that has the same kinematic behavior as the one shown in figure 4. This is explained next.

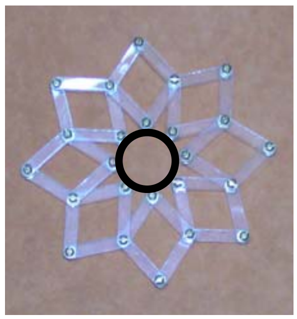
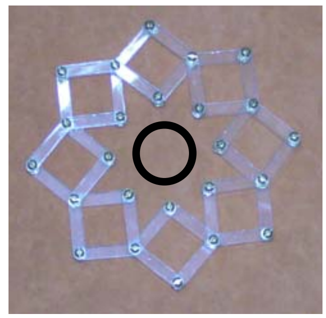
(a)  (b) 

Figure 3. Radially deployable Hoberman's linkage. (a) clamping a pipe externally, (b) releasing the clamp.

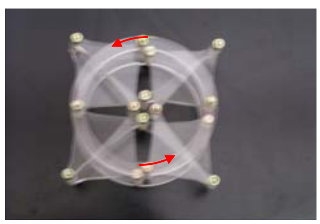
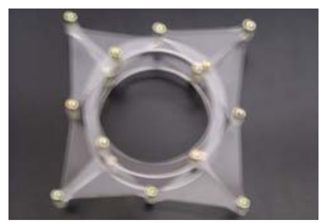
(a)  (b) 

Figure 4. Circumferentially actuated radially deployable linkage from [14]. (a) completely closed configuration, (b) completely open configuration.

2.3 Radially expanding compliant mechanism

Figures 5a-d show the compliant clamp mechanism. As shown in the figure, its interior points move outwards when two of its rings are rotated related to each other. This is derived from the rigid-body linkage shown in figure 4a-b. The circumferential actuation is shown with arrows in figure 4a and how this opens up the interior in figure 4b. Similarly, the compliant mechanism in figures 5a-d has an interior that expands out upon circumferential actuation. It consists of two identical planar layers of certain patterns attached to each other at eight interior points. The two layers are arranged one over the other wherein one is a mirror image of the other about the vertical axis. When the ring portions of each layer are rotated circumferentially relative to each other, the eight attachment points move out radially. To understand the working of this mechanism, consider a single compliant element shown in figure 6a. It consists of two relatively rigid portions (marked P and Q in figure 6a) connected by a slender curved beam of certain shape. Imagine that portion Q is constrained to move along the circumference of a circle whose centre coincides with that of its arcs. Imagine also that portion P is constrained to move along a vertical line passing through the same centre. As shown in figure 6a, the finite element deformation analysis shows that when this element is actuated circumferentially, amplified radial motion ensues. The shape of the slender curved beam is the crucial component for this behavior.

The shape of the compliant segment was intuitively derived by observing the motion of the rigid links of the mechanism of figures 4a-b. A few shapes were explored until satisfactory behavior was obtained. Note that the shape of the slender compliant segments in figures 5 and 6 are not the same. This means that several different shapes give this behavior. The constraints assumed in figure 6a are achieved by using an array of these elements arranged symmetrically around the circumference. A pair of compliant elements attached to each other (so that they are one over the other) is shown in figure 6b. Several such pairs are repeated circumferentially. This leads to the radially expanding compliant mechanism of figure 5 that serves as the pipe-clamping ring. In its un-actuated configuration, it snugly sits on the pipe. Upon actuation, the compliant segments deform outwards and release the clamp on the pipe. The circumferential actuation is easily achieved by an SMA wire wrapped along a circle. The assembly of this specially designed compliant mechanism and the actuating SMA wire constitute one clamping ring of the crawling device. As noted earlier, two such rings exist in the device. They are connected by a linear actuator. We explain the detailed geometry of the ring and the assembly of the whole device in the next section.

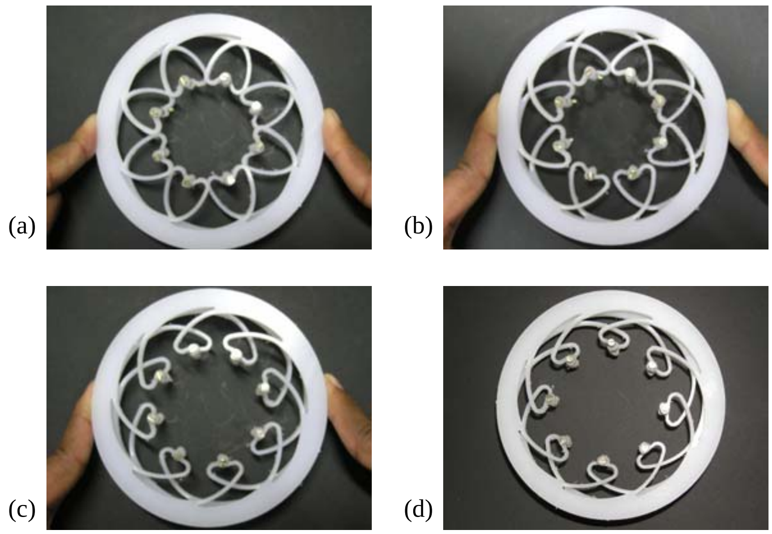


Figure 5. Circumferentially actuated radially deployable compliant mechanism prototype using polypropylene. It consists of two identical layers attached to each other at the innermost points and arranged one over the other. As the rings rotate relative to each other, the attachment points move radially inward or outward. Configuration in (d) is the undeformed while the one in (a) has the most deformation; (b) and (c) are intermediate configurations.

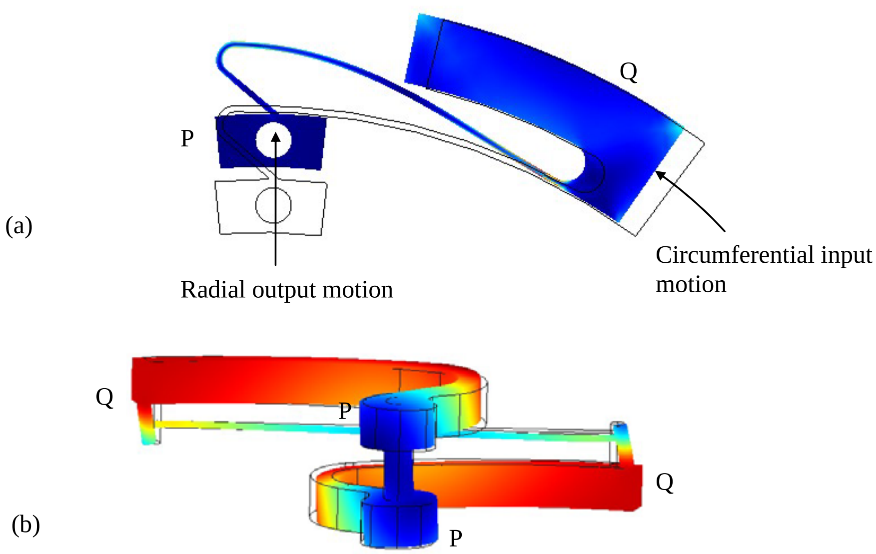


Figure 6. (a) A single compliant element that transforms a circumferential input motion to an amplified radial motion. The filled configuration is the deformed configuration obtained using finite element analysis. (b) Two compliant segments attached to each other and arranged one over the other. Note that the attachment of two P portions automatically constrains the radial movement. By arranging several such pairs along a circle ensures that Q portions move only circumferentially.

3. SMA ACTUATION AND ASSEMBLY

3.1 Detailed design of the clamping ring and the SMA wire actuation

Figure 7a shows a pair of compliant segments that transform the circumferential motion to radial motion. The compliant segments were made out of spring steel (AISI 1080; EN 42J) on a wire-cut electro discharge machine (EDM). Since the two segments are to be in different parallel planes, they were soldered at the point that moves radially as shown in figure 7a. In the real one, to make one clamping ring, we use two rings of the kind shown in figure 7b. We need two clamping rings. So, we made four rings with three compliant segments as shown in figure 7c. The ones in the left column are soldered to the ones in the right column. This gives us two clamping rings each of which has two rings that need to be moved circumferentially relative to each other.

The relative circumferential rotation between the two rings of the compliant clamping ring is easily achieved with SMA wire actuation. We used 0.5 mm diameter Ni-Ti-Cu SMA wire, which is pulled up to 2% strain before it is attached between one point on either of the rings. To facilitate this, we designed a housing to insert the clamping ring and attach the SMA wire.

(a)

(b)

(c)

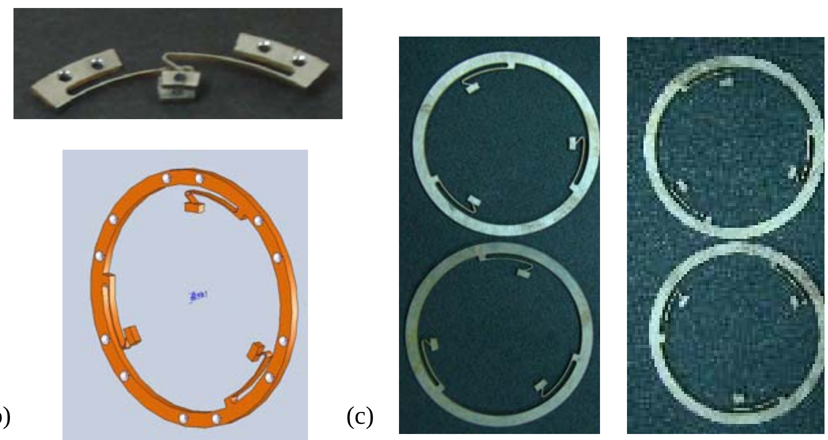


Figure 7. (a) A pair of spring steel compliant segments soldered together. This pair is the main element of the compliant radially expanding mechanism, (b) solid model of a ring with three compliant segments, and (c) four spring steel rings that help create two clamping ring upon soldering of two rings at the interior clamping points.

The housing is made in two halves as shown in figure 8a. Each half of the housing has holes that correspond to those in the ring with compliant segments. These are fastened together. The housing halves were made using aluminium by computer numerically controlled (CNC) milling. These are shown in figure 8b. A solid model of the assembled clamping ring is shown in figure 8c. In the assembled position the two halves of the housing can rotate relative to each other circumferentially. The solid model of the assembled clamping ring snugly fitting over the pipe is shown in figure 8d. Figure 8e shows the clamping ring with the SMA wire. Notice that the SMA wire is inserted into a plastic tube, which sits on a circumferential groove on the aluminium housing. This is because it is necessary to electrically isolate the SMA wire from the housing.

The beneficial interplay between the compliant mechanism and the SMA wire is worth highlighting here. As already stated, SMA wire helps create the circumferential actuation needed to move the clamping points radially outward. This is done by passing current through the SMA wire and achieving the phase-change temperature that makes the SMA wire shrink to its original (memory) length. In this process the SMA wire exerts a stress of about 100 MPa, which for a 0.5 mm diameter wire translates to about 20 N force. Upon cooling, the SMA wire would continue to stay in that length and no further actuation is possible upon re-heating. So, the SMA wire should be pulled back to an increased length. This is done by the compliant mechanism because it acts like a bias spring. Thus, heated SMA wire actuates the compliant mechanism. In turn, when the SMA wire cools and shrinks, the compliant mechanism will pull it back to the stressed (extended) state. Thus, two way motion is possible. This is an advantage of using SMA and compliant mechanisms. The latter serve two purposes: intended motion and biasing stress to keep cooled SMA in the stressed condition.

3.2 SMA strip and bias springs for translational actuation

Figure 9 shows the solid model of two clamping rings attached to each other with U-shaped SMA strips. The SMA wire and the strips were made in the National Aerospace Laboratories, Bangalore. Three SMA strips are attached to the two clamping rings so that the clamping rings can be pushed towards each other upon heating. But then, we also need bias spring strips to push them back when the SMA strip cools. So, provision is made to have three SMA strips and three spring steel strips around the circle. Figure 10 shows the complete device. The testing of this is discussed next.

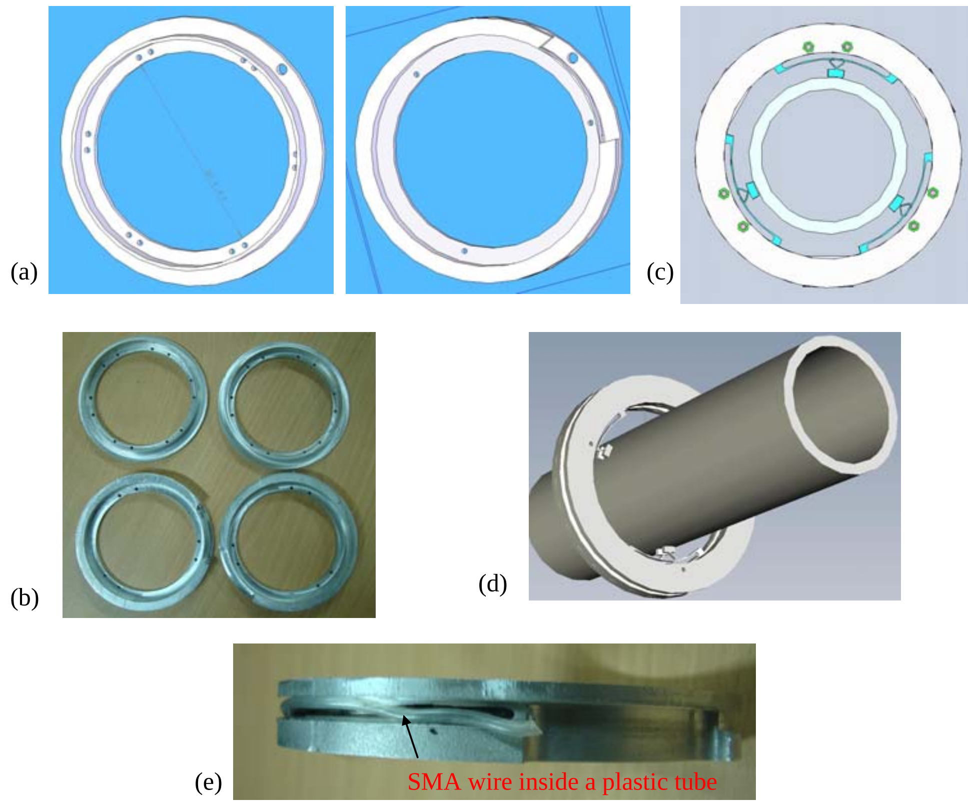


Figure 8. Housing and assembly for the clamping ring. (a) two halves of the housing, (b) two pairs of aluminium housings made using CNC milling, (c) solid model of the assembled clamping ring, and (d) the clamping ring on the pipe.

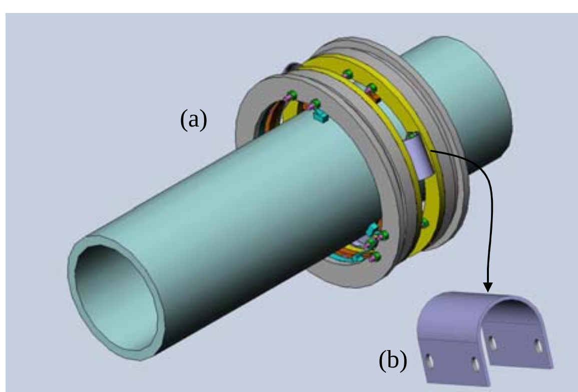


Figure 9. The solid model of the crawling device with the clamping rings and three SMA U-shapes strips. The spring steel bias spring strips are not shown in this picture.

4. PROTOTYPING AND TESTING

The crawling device prototype needs controlled actuation. The SMA wires in the two clamping rings need about 2 A current to move radially outwards by 2 mm. This is enough to release the grip on the pipe whose outer diameter is 54 mm. The SMA strip needs about 4 A current to move by about 3 mm. The thickness (0.2 mm) of the three spring steel U-shaped strips is chosen so that they have enough stiffness to put the SMA strips back into the stressed position. As manufactured and annealed, the “memory” distance between the two arms of the U-shape strip is 18 mm. So, the strips are assembled by pushing the arms outwards to a distance of 21 mm. Thus, the spring steel strips arms are 21 mm apart in their undeformed state. Consequently, the crawler can move 3 mm per cycle.

Figure 10. The complete prototype of the crawling device.

As mentioned in Section 2.1, an inchworm like motion is to be given to the crawling device using cyclical clamping, pulling, and then clamping again. The clamp-and-push cycle consists of the following six steps.

(i) Pass current through the SMA wire of clamping ring 1 to release its grip on the pipe by moving the clamping point radially outward by 2 mm.

(ii) Pass current through the SMA strip to cause linear actuation to bring clamping ring 1 closer to clamping ring 2 by 3 mm.

(iii) Turn off current through SMA wire of ring 1 and allow it to cool to make it grip the pipe again.

(iv) Pass current through the SMA wire of ring 2 to make it release its grip.

(v) Turn off current in the SMA strip to help bias spring strips to recover back to their original length and thus getting an advancement of 3 mm.

(vi) Turn off current in the SMA wire of ring 2 and allow it to cool.

Our experiments have shown that step (i) takes about 10 s. The SMA strip is heated by winding insulated copper wire and passing current through it. This makes step (ii) takes about 30 s. Step (iii) takes about 20 s to completely cool SMA wire 1 so that the first clamping ring grips the pipe again. Step (iv), like step (i), takes 10 s. Step (v) takes about 60 s as the SMA strip has to cool. This step takes longer time because copper wire is wound on the strip and reduces convective heat loss. Finally, step (vi) takes 20 s to cool the SMA wire 2 and close its grip on the pipe. We allow additional 30 s to allow the entire device to cool. Thus, each cycle takes 3 min. Since each cycle advances by about 3 mm, we obtained a crawling speed of about 1 mm/min. It is low but it is a consequence of the need to heat and cool SMA wires and strips.

Figure 11 shows the test set-up. It shows the crawling device staying 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 three clamping points of the two clamping rings, there is enough grip on the pipe. A switched mode power supply (SMPS) of 400 W capacity, routinely used in personal computers, is used to supply a current needed for the SMA wire and strips. Atmel-made AVR micro-controller is used to effect the cyclical operation of triggering the passage and stopping of current in the two SMA wires and one set of SMA strips as per the six steps above. A breadboard circuit that connects the AVR micro-controller and the SMPS is shown as (d) in figure 11.

4.1 Discussion

The complete set-up shown in figure 11 has been tested to make the device crawl on the pipe in the vertical and horizontal conditions. A crawling speed of about 1 mm/min has been recorded on the average. This is very slow but, as noted earlier, the limitation is the SMA strip. It takes about 30 s to heat but 60 s to cool. Using SMA wire wrapped around in some manner to cause linear actuation may help reduce this time. While SMA actuation has this disadvantage, it has an important advantage of being very compact. When we compare the size of our crawler with other crawlers (as discussed in Section 1), our crawler is much more compact. This is partly due to the radially expanding complaint mechanism and partly due to the SMA wire actuation. Other actuations were also considered but they do not come in this compact size. Referring to figure 1, we recall that we only have 10 mm radial space around the pipe. Our prototype currently occupies 25 mm space around the pipe. Our ongoing work is trying to reduce this size to 10 mm. This is done by eliminating the aluminium housing. Even then SMA wire and strip actuation can be used. The strip is the bottleneck to the speed of the crawler right now. A compact solenoid of diameter 8 mm, if available, will solve our problem. But such small solenoids are not easily available. We are currently looking for alternative compact linear actuators to the SMA strip. We are also exploring if SMA wire can be used to effect the linear actuation too. Compact design enables our crawling device negotiate bends on the pipe but we have not tested that yet.

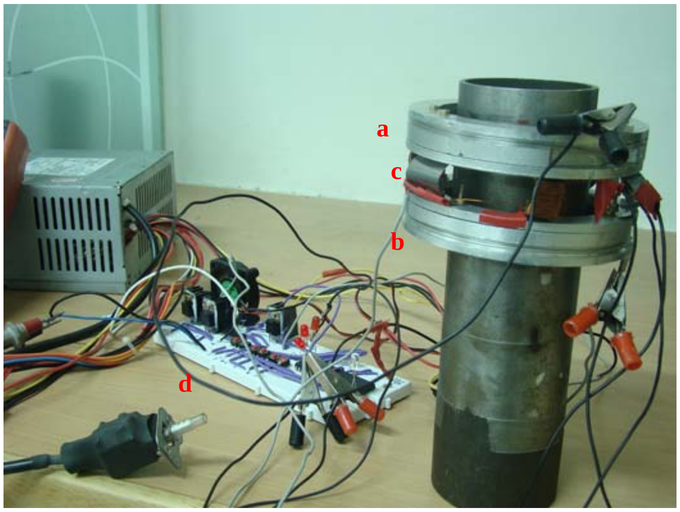


Figure 11. Test set-up of the crawling device. (a) clamping ring 1; (b) clamping ring 2; (c) SMA strip for linear actuation; and (d) control circuit to effect cyclical triggering of the three actuators: two SMA wires and one set of SMA strips.

5. CONCLUSIONS

In this paper, we presented a novel external pipe-crawling device that is very compact. Its compactness is a result of a radially expanding compliant mechanism and (shape memory alloy) SMA actuation. The crawler consists of two clamping rings attached by a linear actuator oriented along the length of the pipe. It follows clamp-and-push cyclical motion of an inch-worm. The compliant mechanism used here was designed on the basis of a kinematic theory developed for radially deployable circumferentially actuated linkages. Circumferential actuation makes the compliant clamping ring mechanism amenable for SMA actuation. A set of three pairs of SMA strips and bias spring strips provide the linear push and pull between the rings. The compliant mechanism is made using spring steel (AISI 1080) by wire-cut electro discharge machining (EDM). The mechanism is housed in aluminium casings milled on a computer numerically controlled (CNC) machine. The SMA wire and strip used in this work were made at the National Aerospace Laboratories, Bangalore. A control circuit is built effects the cyclical triggering in a sequence of six steps. The total cycle time is 3 min and the distance crawled is 3 mm per cycle. Thus, a crawling speed of 1 mm/min was seen in the prototype. It is low and is attributed to the time taken for heating and cooling SMA material. Ongoing work is looking for alternative actuators that are as compact and inexpensive but faster than SMA actuators. The compliant clamping ring based crawling equally applies to internal crawling as it is to external crawling on a pipe.

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7. REFERENCES

1. "Robotic Crawlers," http://www.envirosight.com/products/crawlers.html, 2002.
2. B. Klassen, "Snake 2: A Robot for Difficult Inspection Tasks, Institute for Autonomous Intelligent Systems," ftp://set.gmd.de/pub/SET/publications/released/1999/pdf/Klaassen99.1.pdf, 2001.
3. "NC State Engineers Design Pipe-Crawling Robot to Help Save Lives," *NC State University: College of Engineering News*, http://www.engr.ncsu.edu/news/newsletters/pdfs/coenews.spring00.pdf, 2000.
4. H.T. Roman and B.A. Pellegrino, "Pipe Crawling Inspection Robots: An Overview," IEEE *Transactions on Energy Conversion*, 8(3), pp. 576-583, 1993.
5. F.H. Ghorbel, J.B. Dabney, J.R. Stegar, A. Thomas, P. Spanos, C. Lowry, and B.W. Seto, "Autonomous Robotic Crawler for In-pipe Inspection," US patent 7,210,364 B2, May 1, 2007.
6. A. Zagler and F. Pfeiffer, "MORTIZ, a Pipe Crawler for Tube Junctions," *Proceedings of the 2003 IEEE International Conference on Robotics & Automation*, Taipei, Taiwan, Sep. 13-14, 2003, pp. 2954-2959.
7. J.A. Gálvez, P.G. de Santos, and F. Pfeiffer, "Intrinsic Tactile Sensing for the Optimization of Force Distribution in a Pipe Crawling Robot," *IEEE/ASME Transactions on Mechatronics*, 6(1), pp. 26-35, 2001.
8. D.K. Haas, "Small Diameter Pipe Crawler," *Savannah River National Laboratory Techbriefs*, U.S. patent no. 6,427,602. (follows inchworm motion and gripping feet)
9. P. Breedveld, D. E. van der Kouwe, M. A. J. van Gorp, "Locomotion through the intestine by means of rolling stents," *Proc. 2004 ASME Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, Sept. 28-Oct. 2, Salt Lake City, UT, USA, Paper DETC2004/MECH-57380, 2004.
10. H. Schempf, E. Mutschler, B. Chemel, and S. Boehmke, "BOA II & PipeTaz: Robotic Pipe-Asbestos Insulation Abatement Systems," *Proceedings of the 1997 IEEE International Conference on Robotics and Automation*, Albuquerque, New mexico, pp. 52-59, 1997.
11. C. Hoberman, "Radial Expansion/Retraction Truss Structures", *US patent 5,024,031*, 1991. Also see: www.hoberman.com.
12. Z. You, S. Pellegrino, "Foldable bar structures", *International Journal of Solids and Structures*, 34, pp. 1825–1847, 1996.
13. T. Langbecker, "Kinematic analysis of deployable scissor structures," *International Journal of Space Structures*, 14 (1), pp. 1–15, 1999.
14. J. Patel and G.K. Ananthasuresh, "A Kinematic Theory for Radially Foldable Planar Linkages," *International Journal of Solids and Structures*, 44, pp. 6279-6298, 2007.