An Improved Compact Compliant Mechanism for an External Pipe-Crawler

B.M. Vinod Kumar, Deepthi K. Badige, Sudarshan Hegde, and G. K. Ananthasuresh
M2D2 Lab, Dept. Of Mechanical Engineering, Indian Institute of Science, Bangalore, India
email: suresh@mecheng.iisc.ernet.in

Abstract

An external pipe-crawling device presented in this paper aids the inspection of pipes in hazardous environments and areas inaccessible to humans. The principal component of our design, which uses inchworm type motion, is a compliant ring mechanism actuated using shape memory alloy (SMA) wire. It was fabricated and tested and was reported in our earlier work. But this device had a drawback of low crawling speed (about 1 mm/min) owing to the delay in heating and cooling of the SMA strips in the linear actuation. Additionally, that design also had the difficulties of mounting on pipes with closed ends, large radial span, and the need for housing for electrical insulation and guiding of the SMA wire.

In this paper we present a compact design that overcomes the difficulties of the earlier design. In particular, we present a compact compliant mechanism with two halves so as to enable mounting and un-mounting on any closed or open pipe. Another feature is the presence of insulation and guiding of the SMA wire without housing. This design results in a reduction of the radial span of the ring from 22 mm to 12 mm, and the stiffness of the mechanism and the SMA wire are matched. An SMA helical spring is to used in the place of an SMA strip to increase the crawling speed of the device. A microcontroller-based circuitry is also fitted to cyclically.activate the SMA wires and springs.

Keywords: compliant mechanism, external pipe crawler, Shape Memory Alloy (SMA) wire.

1   Introduction

The motivation for the compact external pipe-crawler considered in this work is the need to move the 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 limited. Typically, for a 50 mm diameter pipe, only 10-12 mm radial space is available around the pipe. This means that we have only annular space between 70 mm and 50 mm diameters. Hence, although there are several options for crawling on the outside of a pipe, we chose the inchworm type motion. Other options are walking with legs, moving with wheels, earthworm-like peristaltic motion, etc. Among these, we found that inchworm motion to give the most compact arrangement.

Inchworm motion takes place with clamp-move-release operations in a sequence with the help of two clamping rings with a linear actuator in between. It is like climbing a coconut or a palm tree by a human being. Along these lines, we designed and prototyped an external pipe-crawler [1]. Figure 1 shows the solid model and Fig. 2 shows the prototype. Fig. 3 shows the complete system that did crawl. In this paper, we improve upon this by overcoming the limitations of the pervious prototype.
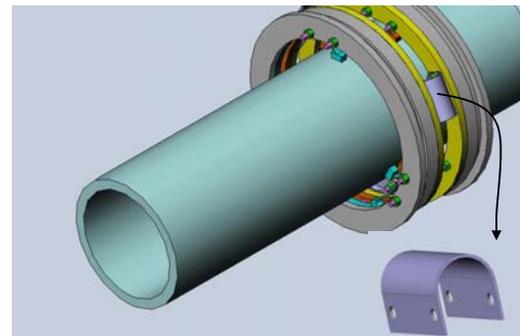
Fig. 1: The solid model of the external crawling device with the SMA-wire actuated clamping rings and three SMA U-shapes strips. The SMA strip is shown in the inset.

The following are the drawbacks of the previous design.
- Low crawling speed (about 1 mm/min).
- Radial span of more than 22 mm while it should be 10 – 12 mm.
- Difficulty in mounting it on pipes with closed ends.

We overcome all the three limitations through design modifications as well as actuation alternative.

Fig. 2: The prototype of the crawling device. It is bulky because of its housing for the clamping rings and is slow because of the SMA strips that take a long time to heat and cool, especially to cool.

Fig. 3: Test set-up of the crawling device with clamping rings, SMA strip for linear actuation and control circuit to effect cyclical triggering of the three actuators, namely, two SMA wires and one set of SMA strips.

The remainder of the paper is organized as follows to clearly present the improvements and the new contributions of this work. In Section 2, we give an overview of our previous design and prototype after presenting some relevant literature to place our work in context. In Section 3, we present the design modifications and prototyping of the mechanical parts. Section 4 describes the electronic interface. We conclude in Section 5.

2 Related and Prior Work

2.1 Related work

There are many crawling devices reported in the literature. Most of these are internal pipe-crawlers and only a few are external crawlers. Even though our device is an external crawler, some of the concepts of the internal crawlers may be useful for comparison. Hence, in Fig. 4, we show different modes of autonomous traversal inside a tube that

we found in our literature search. The first two are obvious: moving with wheel and legs (see, for example, [2]). These two are applicable to crawling outside the pipes too. Inchworm and earthworm modes are most widely used among internal crawlers [3]. See for example, [4] and [5] for these types of internal pipe-crawlers. These modes are also applicable for external crawling. Reference [6] describes an inchworm type external crawler.
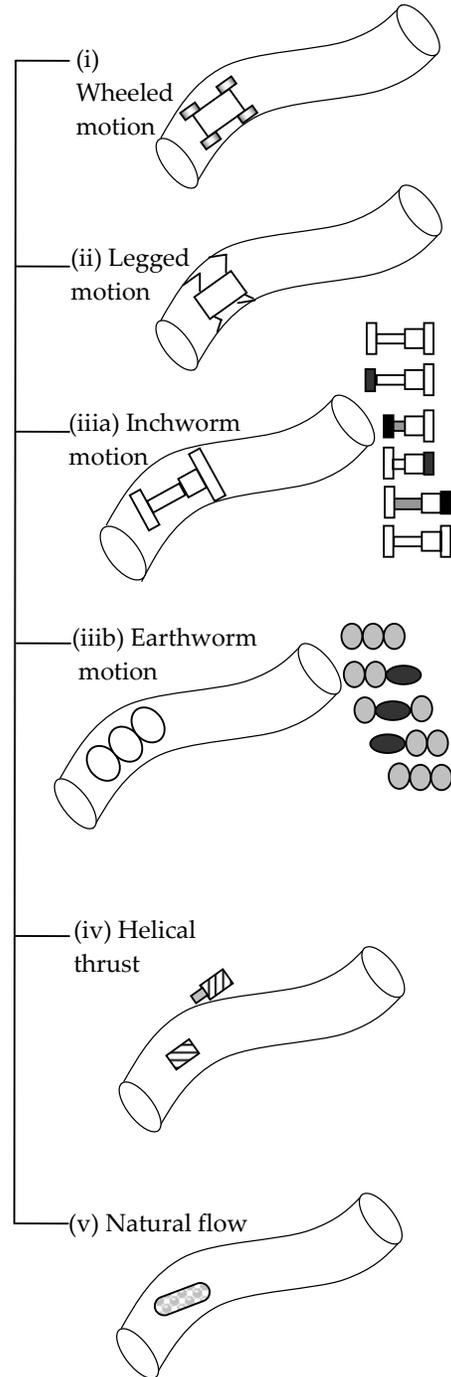
Fig. 4: Modes of autonomous motion inside a tube

Inchworm and earthworm motions may seem the same at first sight but, as shown in Fig. 4, they are different. Inchworm motion is characterized by clamp-move-clamp type of cyclical motion. On the other hand, in earthworm motion, there is peristaltic type standing wave motion along the length of the crawler. Figure 4 also shows an interesting twisting type motion where rotary actuation of a helix creates forward thrust. This is applicable when the tube is filled with some material, either soft solids or fluids. It is somewhat similar to propeller type motion. The twisting motion is explored in [7]. With some modifications, this may be adapted for external crawling too but it does not appear to have been explored. The last mode shown in Fig. 4—the natural motion with flow—is applicable only for internal crawling.

Many factors need to be taken into account in comparing different types of crawling motion. The overriding factor in our case was the available space. We need an external crawling mode that fits within a 10-12 mm annular region around the pipe. This made us choose the inchworm motion because we were able to find a compact compliant mechanism [8] to serve the clamping function around the pipe using SMA wire actuation. We describe our past work on this before presenting the enhancements done in the current work.

2.2 Prior work

As noted above, we had made a case for a compact external inchworm type pipe-crawler in our earlier work [1], which described the analytical basis to our design. We now describe it in sufficient detail to appreciate the improvements made in this paper.

By referring to Fig. 1, we note that the pipe-crawler consists of two rings with a linear actuator in between. There are restoring springs corresponding to the rings and the linear actuator. When there is no actuation, both the rings tightly clamp the pipe. To effect the inchworm motion, the following sequence of actions is necessary: (i) the rear ring releases the clamp, (ii) the linear actuator moves forward, (iii) the rear ring now clamps back and the forward ring releases. This makes the restoring spring of the linear actuator push the crawler one step forward of its initial position. This cyclical operation continues.

For this principle to work in a compact annulus region around the pipe, we used a novel compliant mechanism that enables clamp-and-release of the rings. The compliant mechanism converts the circumferential actuation of a shape memory alloy (SMA) wire into radial motion of contact pads that stay on or off the pipe. The compliant mechanism is a single-piece design. See Fig. 2 to understand how the clamping ring works. Each clamping ring actually has two rings that are joined together at the contact pads. When these two rings are rotated relative to each other, the pads move radially. As can be seen, it is indeed a compact design as opposed to wheels and legs. This concept does not depend on friction to crawl although it may be slightly influenced by it.

The compliant mechanism also acts like a restoring bias spring for the SMA wire. Note that an SMA wire contracts when heated and thus pulling the load. But then to repeat the action in the next cycle, the wire needs to be put back in a stressed configuration. For this, a restoring force is needed. Here, the mechanism itself serves this purpose.

The rings worked well in the previous prototype. But electrical isolation of the SMA wire was difficult. For this, we had used an aluminium housing for the spring steel rings so that the SMA wire does not touch it. A tefflon ring separated the aluminium housing and the spring steel, aluminium, and SMA wire. Consequently, it became bulky in the radial direction (see Figs. 2 and 3). It was as wide as 22 mm bigger than the pipe while its radial extent was to be around 10 – 12 mm.

In between the two clamping rings, there should be a linear actuator. For this, we tried using U-shaped SMA strips specially made for this purpose. The U-strip would contract and bend its two beams and pull them closer, and thus move the crawler forward. But a problem arose in heating the SMA strip. It has low electrical resistance and hence draws a lot of current. It also takes a lot of heat to raise its temperature for SMA to undergo phase-change. More severe is the problem with cooling. We had wound insulated copper wire (0.5 mm in diameter and 2 to 3 m long) around the U-strip. Heating and cooling the strip takes about a minute. So, in about a minute, one cycle of inchworm motion is finished. But the movement in one step is only 1 mm. Hence, we achieved a speed of 1 mm/min.

As can be seen in Fig. 2, the rings cannot be mounted if the pipe is closed on both the ends. So, we move to four contact pads as opposed to three. If there are four pads, there is symmetry in the design and hence it can be made in two halves and then assembled.

Having explained each of the three limitations, we now present our design and prototyping modifications.

3 Modified Design

In addition to describing the design modifications in this section, we also present the finite element analysis (FEA) calculations that were necessary to ensure the matching of the stiffness of the SMA wire and the compliant mechanism. This also warranted proper characterization of the SMA wire,

which is also presented here.

3.1 No housing

To reduce the radial distance, the housing of the previous design is eliminated. This results in a reduction of the radial span of the ring from 22 mm to 12 mm. The new design of the clamping ring is shown in Fig. 5. It consists of two identical rings with compliant arms at the ends of which contact pads are provided. The two rings are joined to each other at the pads using soldering. There is a 6 mm long spacer between the two contact pads in the axial direction of the rings. In order to obtain radial motion of the pads, we need to rotate the two rings relative to each other. We use SMA wire for this purpose. There are two difficulties here.

The first difficulty is that the SMA wire through which the electric current needs to be passed for heating it, should not touch the ring. Providing this insulation is therefore essential. The second difficulty is that the SMA wire straightens when it is heated. So, if we do not guide it circumferentially, it will tend to cause relative translation of the two rings rather than rotate them relative to each other. Finite element analysis presented later in the paper confirmed this. Note that a compliant mechanism has many degrees of freedom as opposed to a rigid-body linkage. The one here has additional degrees of freedom and they come into play if the force acts in those ways. So, we must constrain the SMA wire to stay inside a circumferential tube. Insulation and guiding are explained next.

3.2 Insulation and Guiding

The SMA wire is inserted inside a Tygon tube which insulates the SMA wire from the spring steel compliant ring mechanism. To further insulate the SMA at the ends, the Tygon tube with the SMA wire is inserted into two terminal guide blocks. This block is a short circumferentially profiled piece with a hole. It is attached to both the rings using non-conducting adhesive material.
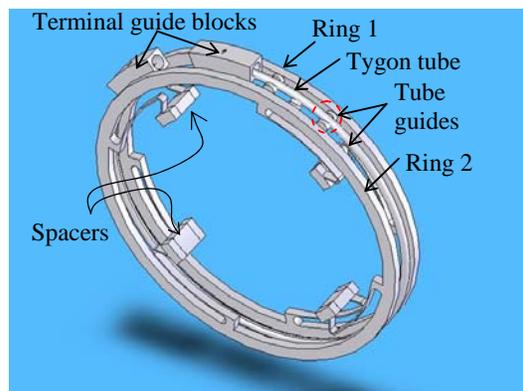
Fig. 5: The solid model of the compact design of compliant clamping ring that does need a housing.

To guide the Tygon tube, and with it the SMA wire, along the circumferential direction, a number of small spring steel cylinders of 3 mm in diameter and 5 mm in length with a 1.3 mm deep semi-cylindrical cut on the cylinder's body (see Fig. 6), are used. These are fastened to the rings using an adhesive. These, marked as 'tube guides' in Fig. 5 are alternately provided on the two rings with a spacing of 6 mm. A close-up view of the tube guide is shown in Fig. 6.
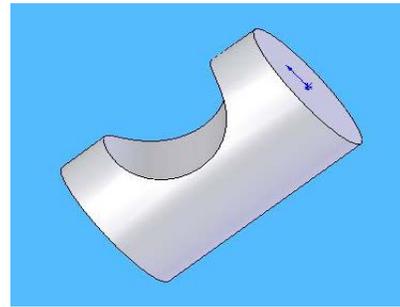
Fig. 6: Solid model of spring steel guide for the SMA wire.
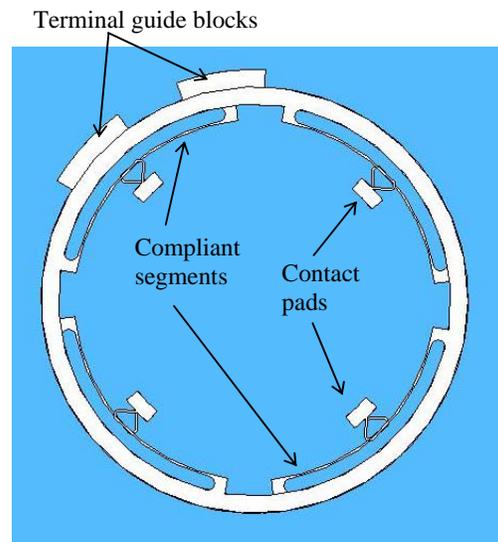
Fig. 7: Top view of the new compliant ring with four contact pads that rest on the pipe for a grip.

3.3 Symmetric design

To provide symmetry in the clamping ring, we have provided four gripping pads instead of three gripping pads which were used in the previous design. See Fig. 7. As a consequence, the ring can be made in two symmetric halves and hence it can be mounted on a pipe whose ends are closed or otherwise inaccessible. This change requires re-design of the compliant segments that convert circumferential SMA wire actuation into radial motion of the contact pads. There are two aspects to this: determining the stiffness of the

SMA wire and matching the stiffness of the SMA wire that of the compliant mechanism. These are described next.

3.4 SMA wire characterization.

Although SMA wire-actuation is slow, it is proffered because it occupies small space and low speed is not that big a constraint for the 'crawler'. No other actuation is this compact and can provide large force and remains inexpensive.

The principle of using SMA actuation is shown in Fig. 8. It shows that the SMA spring (wire, strip, or any other geometry) stretched from its 'memory shape' at room temperature and connected to a load or bias spring. Since SMA exhibits pseudo-plasticity in this condition, it stretches and stays that way. After this the SMA wire is heated so that it can return to its memory shape and pulls the load or bias spring in this process. When the SMA wire cools down, it is the load or the bias spring that pull the SMA back to the stressed state. Otherwise, re-heating does not make any further movement. Thus, the load or bias spring plays a crucial role here. If the bias spring is not stiff enough, the SMA wire does not return to the sufficiently stressed state and hence the stroke of actuation will be reduced. If the load/bias spring is too stiff, the SMA will give a very small stroke.
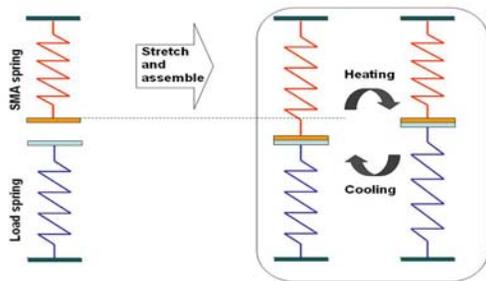
Fig. 8: Actuation of SMA wire with load/bias spring.
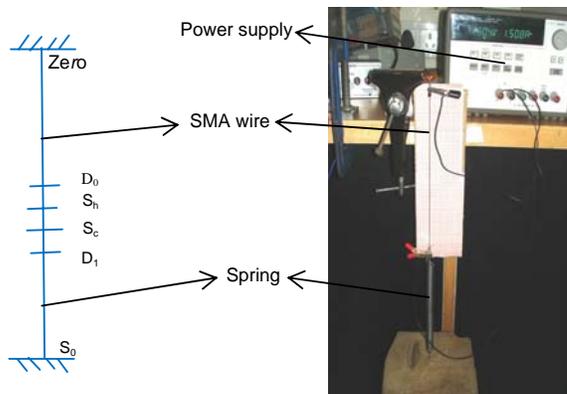
Fig. 9: An experimental setup to find the matching stiffness of the SMA wire.

In the crawler design, the compliant clamping ring itself acts as the load as well as the bias spring. In order to match its stiffness with that of the wire, we performed an experiment with the SMA wire with seven springs that are bought off-the-shelf. The setup is shown in Fig. 9. It consists of an arrangement to connect the commercial springs, one at a time, to the SMA wire that has electrical connection to heat it using Ohmic heating. There is a provision for measuring the extension/contraction of the spring and the SMA wire. Some particulars and symbols used in the left side of Fig. 9 are as follows:

Stress in SMA wire = 100 MPa
Free 'memory' length of the SMA wire, D_0 = 22.6 cm
After elongation = D_1 = 23.2 cm
SMA wire diameter = 0.5 mm
S_0 = distance from zero to the bottom of the spring
S_h = the length of SMA wire after heating
S_c = the length of SMA wire after cooling

The measurements were taken for all the seven springs and the readings were noted. See Table 1. The spring constant and the free length of the springs are also shown in the table.

Table 1: Experimental readings of the SMA wire.

No.	Stiffness (N/m)	Free length (cm)	S_0 (cm)	S_h (cm)	S_c (cm)
1	3090	2.6	22.6	22.7	23.2
2	5500	6.3	29.9	22.7	23.2
3	950	8.0	31.6	22.6	23.2
4	270	9.0	32.6	22.6	23.1
5	300	10.0	33.6	22.6	23.1
6	520	10.2	33.8	22.6	23.1
7	1520	16.8	39.1	22.7	23.2

But the SMA wire behaves differently when it is in a straight and when it is bent along the circumference of a circle. Finite element analysis is done to investigate the deformation behavior of the mechanism.

3.5 Finite element calculations

A detailed 3D finite element analysis of the crawling mechanism was done using ABAQUS finite element software (see Fig. 10). Except for the SMA wire, all the other entities of the mechanism were incorporated into the model.

The region of actuation of the mechanisms by the SMA wire was also taken into account in the model. Geometric nonlinearity was incorporated in the analysis. A few important observations were made in the analysis.

A force of 18 N is required to obtain a deflection of 1 mm in the circumferential direction. When the two actuation points move circumferen-

tially by a distance of 1 mm each, the radial deflection observed in the resting pads is not the same for all the pads (see Fig. 11). This was also observed experimentally in the prototype (see Section 4 for the prototype).
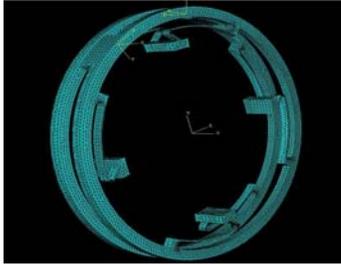
Fig. 10: The meshed model of the mechanism.
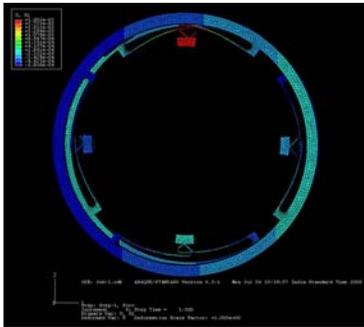
Fig. 11: The y-displacement shows the radial displacement of the jaws placed at 90° and 270°.

    The pad which is closest to the region of actuation deflects the most. The pad which is diametrically opposite to this deflects the least. The magnitude of deflection of the other two resting pads is in between (see Fig. 11 and Fig. 12). This could be attributed to the following two reasons:

i. The two circular rings no longer remain concentric (see Fig. 11 and Fig. 12).
ii. The two rings no longer remain parallel but move out of plane after deformation (see Fig. 13).

The first one was observed in the prototype but the second one was not. This is because, once the clamping ring is mounted on the pipe, certain additional restrictions exist as a result of further provisions that prevent. Here, contact takes place between the Tygon tube and the ring. This is not modeled in FEA. These additional features are too small to see in the photographs presented in the next Section, which describes the prototyping.
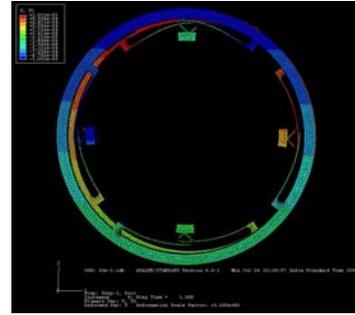
Fig. 12: The x-displacement shows the radial displacement of the jaws at 0° and 180°
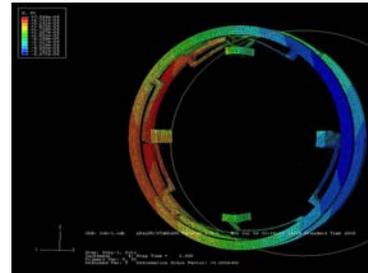
Fig. 13: The z-displacement shows different contours in different regions indicating that the two rings do not remain parallel after actuation.

4 Prototyping and Testing

The design of the compliant mechanism rings and other parts such as aluminum and spring steel guides were designed in SolidWorks and ELAPT software was used for G-code generation for wire-cut Electro Discharge Machining (EDM). The assembly of the compliant mechanism is shown in the Figs 14, 15 and 16. The two compliant rings with the spacer are fastened by soldering. The ring works by gripping the pipe when it is vertical and slipping off when actuated as the contact pads loosen the grip by moving out radially.

Fig. 14: Compact compliant clamping ring
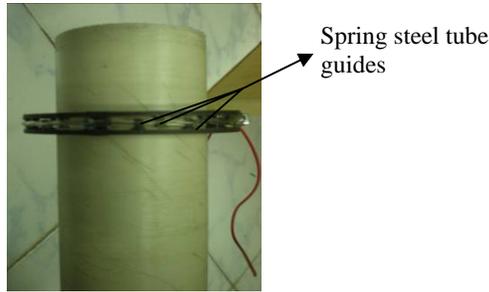
Fig. 15: The clamping ring on the pipe in the vertical position with marked spring steel guides.

Fig. 16: The clamping ring on the pipe in vertical position with marked alumunium terminal blocks that electrically insulate the SMA wire's ends.

5   Electronics and Integration

Linear actuation between the two clamping rings is the main component for crawling. In our earlier version, we had used a U-shaped SMA strip which took a lot of time to heat and cool. Furthermore, a wire had to be wound on the strip to heat it. So, we decided to change the linear actuator to an SMA helical spring. The SMA spring is made out of an SMA wire in the form of a helical compression spring. When it is heated by supplying a pre-calculated amount of current, it gets compressed and brings the clamping rings closer together. There are bias springs that will move the rings apart to their initial stressed state upon cooling. (see Fig. 17). The SMA spring should provide a force of 25 N for linear actuation for 5 mm traversal as the calculated stiffness of spring steel compression spring is 5 N/mm.

An electronic board is necessary to make the device shown in Fig. 17 crawl. Eelectric current has to be supplied to the two SMA wires that helps the clamping rings release their grip, and make the linear actuator between the two clamping rings move relative to each other. This requires a driver circuit to cause these actuations happen cyclically.

The current-driving circuit (see Fig. 18) on a printed circuit board is used to effect the cyclical operation of triggering the passage and stoppage of

Fig. 17: Completed prototype with two clamping rings, linearly-actuating SMA springs, and bias springs. The SMA springs are shown extended.
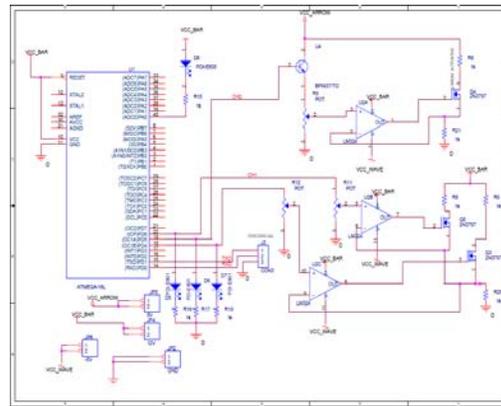
Fig. 18: Electronic schematic diagram for cyclic operation of the mechanism.
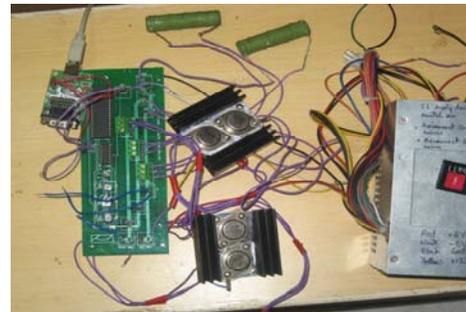
Fig. 19: Complete electronic circuit on printed circuit board with SMPS shown.

current in the two SMA wires and one set of SMA helical spring used for linear actuation. The circuit has Atmel-made AVR microcontroller with three current sources in parallel as shown in Fig. 19. A switched mode power supply (SMPS) of 400 W capacity that is taken from a personal computer, is used to supply a current needed for the SMA wire and linear actuating SMA helical spring. The current can

be switched by the microcontroller and the value of current can be set by the three potentiometers. High- power MOSFETs are used to get the current loads required for the actuator. The microcontroller is interfaced by USB serial converter. A command-driven program is used to set the various actuator timings. The sequence of the actuation is programmed into the microcontroller so that switching of the actuators is automatic.

With all these improvements, the crawler can now move at 5 mm per minute. We observed that it takes about 30 s to heat and cool the SMA springs, which is the time-limiting step. The actuation of the clamping rings takes only a few seconds.

5   Closure

This paper is concerned with an external pipe-crawler that has to fit within an annular space of 10-12 mm around a pipe of about 50 mm outer diameter. We used the inchworm type motion with two compliant clamping rings with a linear actuation in between. In this paper, we presented improvements made to our previous design of an external pipe-crawler by overcoming its three limitations. The first is reducing the radial space from 22 mm to 12 mm. The second is avoiding housing for the compliant clamping rings and yet providing electrical insulation between the actuating SMA wires and spring steel clamping rings. The third is doing away with the U-shaped SMA strip and introducing the SMA helical spring to increased the crawling speed from 1 mm/min to about 5 mm/min. Several details of the design including finite element analysis and driving electronics are presented.

Acknowledgment

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