A SMA Actuated Artificial Earthworm

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Abstract—**This paper presents the design and development of a microrobot which aims to replicate the locomotion principle of earthworms. The undulatory locomotion of living earthworms has been investigated deeply from the biological point of view, but attempts of replication of earthworm models in real size are limited. The authors designed an artificial earthworm with four modules which can be driven independently according to defined undulatory patterns with a typical frequency of 0.5 Hz. Each module is actuated by one or more SMA springs whose configuration has been designed in order to limit the wiring problems and optimizing working frequency. The robot is covered by a shaped silicone material which can be used as a platform to insert tiny legs for obtaining differential friction conditions. Preliminary tests demonstrate that the earthworm prototypes can move with a speed of 0.22 mm/s, thus approximating the behavior of biological earthworms.**

Keywords-microrobot; SMA actuators; undulatory motion.

I. INTRODUCTION AND MOTIVATIONS

An increasing research and literature exist on the understanding and replication of motion abilities of animals which look propelling efficiently in different environments where normal propulsion systems (e.g. wheels) fail [1, 2]. The typical applications of these researches range from rescue robotics, to industrial inspection and to the field of medical endoscopy [3, 4].

In particular the authors moved from the medical field: they developed robots for semiautonomous colonoscopy by taking inspiration from the inchworm locomotion of some insects and parasites (e.g. leeches) [5]. After a deep analysis of the typical performance reachable by following a mere bio-inspired approach and after comparing these performance with typical performance of biological creatures, they gradually moved from a bio-inspired to a biomimetic approach [6]. The goal is really improving efficiency of locomotion by understanding the motion mechanisms of some animals -such as the earthworm- whose locomotion can be approximated by an inchworm motion.

The real replication of an earthworm should consider not only locomotion mechanisms, but also perception systems and neural control, together with the enabling technologies to reach such a type of "imitation". This paper illustrates a first step towards the realization of an artificial moving platform designed to replicate the locomotion mechanism of living earthworms. Hopefully, the artificial moving earthworm will constitute a platform for improving the knowledge of mechanisms regulating motion and perception abilities of these creatures.

II. THE BIOLOGICAL MODEL: THE EARTHWORM

During burrowing, earthworms squeeze the anterior end forward into the soil by pushing against other parts of the body that serve as anchors. The anterior segments then expand as a new anchor that helps pull forward segments behind them. A simple system of surrounding muscles and a hydrostatic skeleton create these undulatory movements. In fact, body segments are composed by longitudinal muscles and circular muscles: when the circular muscles contract, decreasing the segment diameter, segment length must necessarily increase, in order to let the segment volume constant. Similarly, when the longitudinal muscles contract, thus decreasing segment length, segment diameter must necessarily increase. In order to improve locomotion and borrowing efficiency, the segment surface is endowed with setae (generally 8 per segment). When the segment diameter is enlarging, the setae extend outward to help anchor the worm to the ground surface where it is moving (Fig. 1).

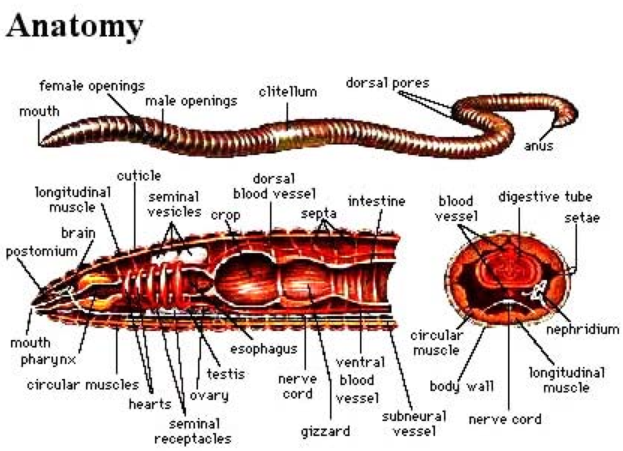

Figure 1. Anatomy of the earthworm (*Lombricus Terrestris*).

Characterization of the earthworm motion has been carried on by biologists, thus producing an interesting set of specifications for possible artificial replications [7, 8].

Experimental observations demonstrate that worms have different speed and elongation/circumferential strains depending on their mass. Generally, large earthworms crawl at a greater absolute speed than small earthworms, but at the same relative speed if normalized to the body length.
Body wall strains are independent of body mass: the segments elongated by approximately 60% during circumferential muscles contraction and they narrow by approximately 25% during circumferential muscle contraction. Stride (distance traveled during one cycle of peristalsis) frequency has a slight dependence on mass: approximately stride frequency for small earthworms (about 1 g) is 0.25 Hz.

III. Design of The Artificial Earthworm

The crucial problem in the design of an artificial earthworm is related to the selection of a suitable actuator to produce one module which can elongate of about 60% and contract of about 25%, thus keeping approximately constant the volume of the module itself. In fact, each earthworm segment has it is own discrete, fluid-filled compartment, although the central coelum plays a role or rigid structure for excretion.

On the basis of the required performance, the selected actuator has been shape memory alloy (SMA) [9 - 11]. SMA wires with a length contraction of 4% can achieve deformation 100 times larger when used in spring configurations. Obviously the force in wire configuration is 15 times larger than in spring configuration. However, the force reduction is acceptable because there are not stringent constraints about forces (the borrowing and locomotion ability depends on setae geometry and friction properties rather than module force). The design of the artificial module is shown in Fig. 2.

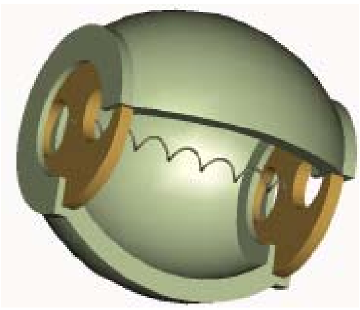

Figure 2. Earthworm module.

The module is 1 cm in diameter and approximately 1 cm in length. SMA springs (one or three per module) link two brass disks which are connected to electrical wires. The spring diameter obtained by 100 µm in diameter wire is approximately 600 µm; the spring diameter obtained by 50 µm in diameter wire is approximately 350 µm. The antagonistic structure for the SMA spring consists of a silicone shell. When current is established between the two disks, the SMA spring is heated for Joule effect and contracts (austenitic phase), thus bending the silicone shell. Once removed the current, the SMA spring turns to the plastic phase (martensitic phase at low rigidity), the silicone shell can recover its original shape, thus pulling the SMA springs to the original length.

By considering the parallel with segments of biological earthworms, the artificial module possesses *active* longitudinal muscles and *passive* circular muscles.

In order to optimize the module parameters, a finite element analysis (FEA) of the module has been carried on by ANSYS 6.0, as illustrated in Fig. 3.

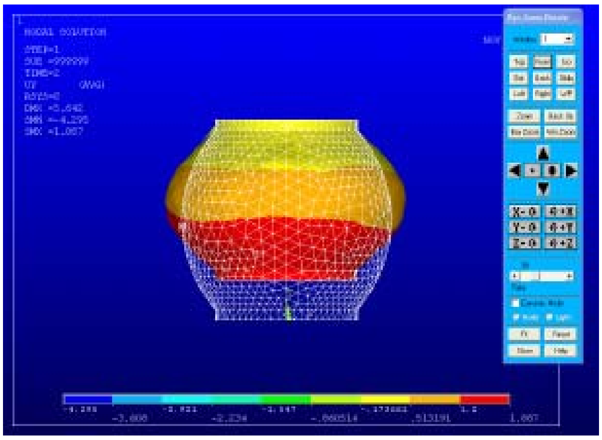

Figure 3. Module deformation with displacement of 2 mm (single spring configuration; SMA wire diameter of 100 µm; Silastic 3483 silicone shell).

For the simulation, we have considered Silastic 3483 silicone (produced by Dow Corning, USA) and a SMA spring fabricated by wires 100 µm in diameter (050 LT Muscle Wires ® by Mondo-tronics ®).

Two different configurations for the SMA springs have been considered: the first one consisted in 3 springs in parallel for each module, fabricated by 50 µm in diameter SMA wire; the second one consisted in one single spring for each module, fabricated by 100 µm in diameter SMA wire. The 3 springs in parallel have been initially preferred in comparison with the single spring configuration for the following reasons:

- the cooling time of a 50 µm wire is much shorter than the cooling time of a 100 µm wire. Practically the time is shortened down to one half or less (experimental tests demonstrate that the cooling time can be shortened of a 2.5 factor); this assures better overall performance in terms of driving wave frequency;
- the force generated by 1 spring with wire diameter of 100 µm is about 0.3 N, thus bending virtually any silicone shell. This force can be reached also by the parallel of more springs (in particular 3 springs) with lower diameter;
- moreover, 3 springs in symmetrical configuration limit not-axial deformation which could be generated by spring fabrication inaccuracies or substrate irregularities.

As illustrated in the following paragraph, the final tests have been performed by using the single spring configuration, because of its better reliability and its simpler assembly.

The circumferential arch profile of the silicone shell has been studied in order to produce a bending directionality towards the external part of the module. From the FEA simulation we have obtained an optimal thickness of 0.8 mm for the silicone shell.

IV. FABRICATION OF THE ARTIFICIAL EARTHWORM

The fabricated earthworm prototypes consist of 4 modules and 5 disks. Additional modules have been considered in order to better replicate real earthworms, but they have not been implemented essentially for wiring problems, as illustrated below.

The disks are fabricated in brass, in order to assure the electric contact between the springs and the disks. An electrical wire with diameter of 127 µm is soldered to each disk, thus producing a robot tail of 5 electrical wires with total diameter of 635 µm.

In the 3 springs configuration, the 12 springs of the 4 modules are obtained by one single SMA wire which is shaped in straight and spring sectors and thus it is threaded into the disk holes. The fixing process of the SMA wire to the hole of the brass disk is very critical: the fixing must assure the perfect electrical connection between the SMA spring and the disk; moreover, mechanical fixing is not adequate because it introduces deformation in the springs and mounting irregularities. After different attempts, the most reliable solution has been the fixing by electrodeposition of conductive material (copper) inside the hole of the brass disk (Fig. 4).

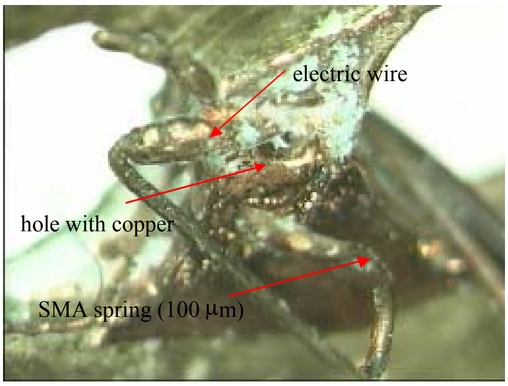

Figure 4. Disk with electrodeposited copper for electrical contact.

By growing copper in the hole, two additional results are obtained:

- reliable fixing between spring and disk without local deformation of the spring;
- a *heat sink* between spring and disk allowing a faster thermal exchange.

The poor stability of the copper around the 50 µm SMA wires and the difficult implementation of the above procedure in the 3 springs configuration led to the implementation of single spring artificial earthworms for extensive testing.

Fig. 5 shows the internal SMA mechanism of two artificial earthworms with 3 springs configuration and single spring configuration.

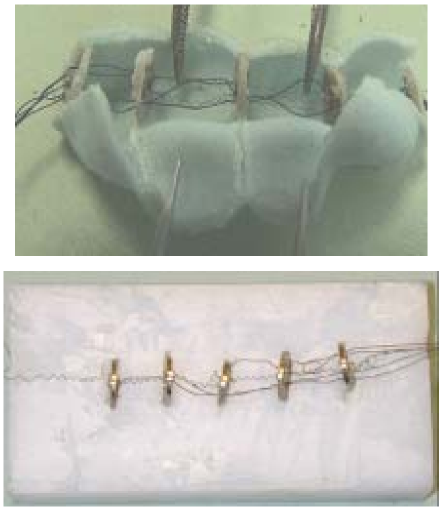

Figure 5. Earthworm skeleton: 3 springs modules (top); 1 spring modules (bottom).

The silicone shell is obtained by moulding. A stereolithography mould has been fabricated in Nylon. It consists of 3 pieces: the internal core and two symmetrical moulds, as illustrated in Fig. 6.

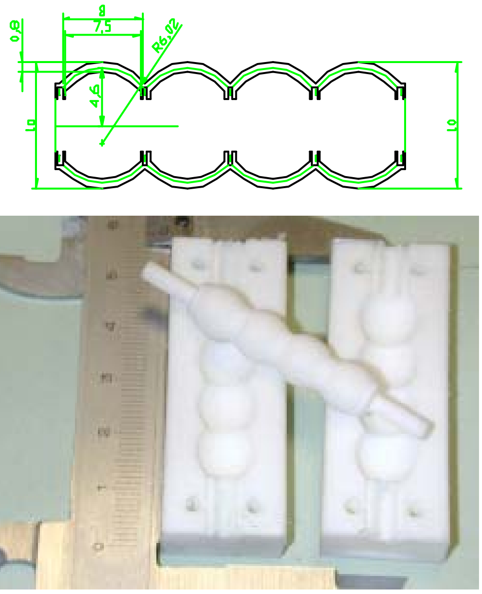

Figure 6. Earthworm mould: drawing (top) and prototype with internal core (bottom).

The gap between the core and the external mould is 0.8 mm, thus allowing to obtain a silicone thickness compatible with the results of the FEA. The main advantage of the moulding technique is that it allows to test different silicones for the shell fabrication: in fact, theoretical simulations are not always fully reliable, because of the difficulty to find the correct parameters of the silicones (e.g. differences of 50%

between the expected and the real behavior of silicone structures are ordinary). Finally, the SMA mechanism is inserted into the silicone shell and the disks are glued to the internal part of the shell, thus obtaining the structure illustrated in Fig. 7.

Figure 7. Artificial earthworm prototype.

A. *Artificial Earthworm Control*

The driver strategy consists of producing a sequential contraction of the modules. Each module is activated by a square periodic signal, as illustrated in Fig. 8. The typical current provided to each module is about 600 mA.

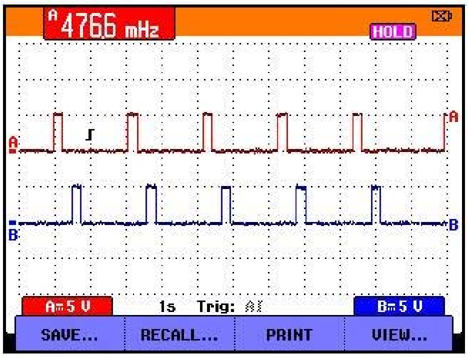

Figure 8. Activation sequence of two contiguous modules (A and B) where the delay is shown.

The typical period of one cycle (sequential activation of 4 modules) is about 2 s. The current peak duration is about 210 ms and the activation delay between two contiguous modules is about 320 ms, which is the time needed to cool the SMA spring and to recover the elongated configuration. It is possible to increase the working frequency more than the typical value of 0.5 Hz, but with the risk to generate thermal saturation in the springs.

The locomotion sequence is obtained by a microprocessor (PIC16F84) according to the architecture illustrated in Fig. 9.

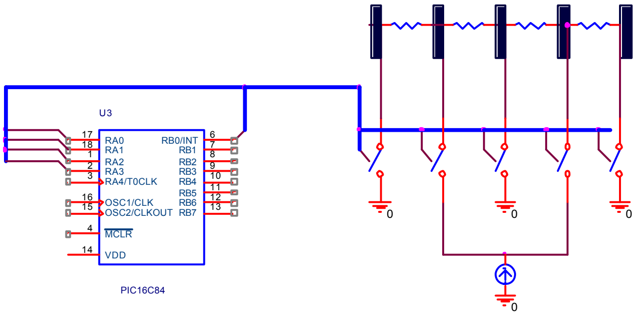

Figure 9. Earthworm control scheme.

V. LOCOMOTION EXPERIMENTS

The advance of biological earthworms is realized by the differential friction of the enlarged modules as regards the elongated modules, by the protrusion of the setae -which improve the anchoring mechanism- and by inertia effects. The total mass of the earthworm and the ratio between the mass of the protruding segments and the mass of the anchoring segments can explain the net propulsion of earthworms [8]. An intrinsic limitation of the artificial earthworm is the low number of segments and the low mass, which do not allow to observe effective inertia phenomena, neither to implement complex combinations of traveling waves driving the structure. In fact, once actuated the locomotion sequence onto a flat surface, the net displacement of the mini-robot is negligible: the structure contracts and elongates sequentially the modules without producing any organized net propulsion.

In order to produce a net displacement two complementary methods have been followed: the first one consists of the fabrication of tiny directional legs (mimicking the biological setae), thus producing differential friction during elongation and retraction phases of the segment (Fig. 10); the second one consisted of propelling the robot onto a directional surface, such as a velvet surface.

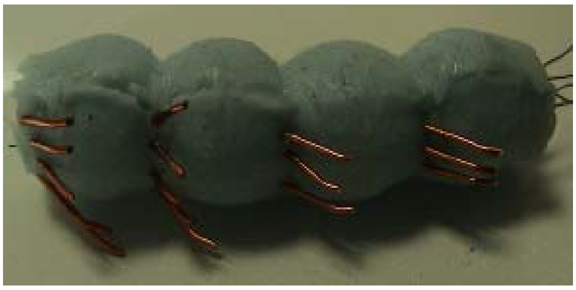

Figure 10. Legged artificial earthworm. The legs, mimicking the setae, are 500 µm in diameter.

The velvet surface consists of clusters of fibers with lenght of 800 µm and diameter of 50 µm. The fibers are oriented and partially superimposed, thus producing a periodic structure of about 550 µm (Fig. 11).

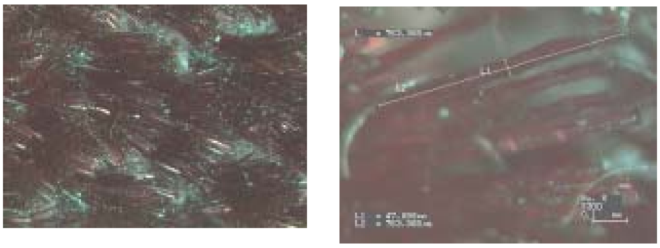

Figure 11. Velvet-like surface. Left: magnification of 50X; right: magnification of 300X.

The performance of the legged earthworm on a flat surface are difficult to be measured because the locomotion sequence is not regular, due to inaccuracies in the fabrication and mounting of the setae. On the other hand, the locomotion sequence on the shaped surface is very efficient and regular: the periodicity of the velvet substrate plays the role of organized setae and helps the earthworm to generate differential friction areas between the shell and the substrate, thus allowing a net directional propulsion.

Table 1 shows the experimental parameters used to characterize the earthworm locomotion on the shaped substrate and the final results.

TABLE I. EARTHWORM VELOCITY

Frequency (mHz)	Current peak duration (ms)	Current (mA)	Energy for module (J)	Measured velocity (mm/s)
162	670	433	0.44	0.11
250	480	500	0.42	0.17
470	320	600	0.40	0.22

By increasing the cycle frequency, the current peak duration must decrease, in order to keep approximately constant the delay time between two contiguous activated modules (i.e. the cooling time). Thus, the current delivered for each peak must increase, in order to keep the power consumption per module and the module deformation approximately constant. The Joule effect energy (fourth column) is obtained by considered a spring resistance of 3.5 ohm.

Figure 12. The artificial earthworm climbing the sloping velvet surface.

The maximum locomotion force has been measured during the climbing of the earthworm onto a sloping velvet surface, by avoiding that the tail interfered with the robot motion (Fig. 12). The locomotion parameters have been set as in the last line of Table I. Then the velvet surface has been gradually tilted until the robot stopped (25°). By considering the mass of the earthworm, which is 1.4 g, a maximum locomotion force of 5.8 mN has been measured.

VI. CONCLUSIONS AND FUTURE WORK

The SMA actuated artificial earthworm has demonstrated encouraging results in terms of speed and activation frequency. A key problem which should be addressed for improving the locomotion efficiency is related to the implementation of micro-legs which could increase the differential friction during the contraction and elongation phases of segments. Silicone micro-legs could be obtained directly during the moulding of the external body, also exploiting a material with different rigidity. An additional improvement consists of designing modules with 3 independent springs, which would allow the robot to steer: each segment could work as a parallel mechanism, thus reproducing the steering ability of living creatures. On the other hand, the wiring problems is a critical constraint, as illustrated in section IV.

In order to fabricate an earthworm robot with many segments - thus allowing to make a real comparison with biological creatures - a system approach is needed. The idea is to couple "autonomous" segments, each including:

- a legged shell;
- 3 springs mechanism, allowing contraction and bending;
- on-board driver;
- identification buffer (1 byte allows to address 64 modules, integrating 3 springs per module)
- 4 connection wires between contiguous modules.

Then, by exploiting a microcontroller located at the robot tail, each module can be driven by an asynchronous transmission protocol.

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