Proceedings of the 2004 IEEE
International Conference on Robotics and Biomimetics
August 22 - 26, 2004, Shenyang, China

Design, Fabrication and Performances of a Biomimetic Robotic Earthworm

A. Menciassi[1], S. Gorini[1], G. Pernorio[1], Liu Weiting[1,2], F. Valvo[1], P. Dario[1]

[1] Scuola Superiore Sant'Anna
Center for Research in Microengineering – CRIM Lab
P.za Martiri della Libertà 33, Pisa (Italy)
arianna@sssup.it
[2] Zhejiang University
Zheda Rd 38, 310027, Hangzhou (China)

***Abstract*—This paper presents the design and development of a microrobot which aims to replicate the locomotion principle of earthworms. By investigating the biological field, the authors developed artificial earthworms by mimicking the structures and locomotion principles of real ones. Prototypes with or without micro-legs (which affect the locomotion performance) have been developed. Each prototype has 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 robots are covered by shaped silicone material which can be used as a platform to insert tiny legs for obtaining differential friction conditions. Preliminary tests demonstrate that the maximum speed of earthworm prototypes can reach 0.22 mm/s without micro-legs and 2.5 mm/s with micro-legs, thus approximating the behavior of biological earthworms.**

***Index Terms*—microrobot, SMA actuators, undulatory motion, micro-legs.**

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 locomotiom 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 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.

The activity presented in this paper has been carried on with the support of the European Commission, in the framework of the BIOLOCH Project (BIOmimetic structures for LOComotion in the Human body – IST FET Programme, IST-2001-34181).

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. In order to improve locomotion and burrowing 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.

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

A large number of body segments allows to generate complex peristaltic waves which enable locomotion also without grasping/anchor points (Fig. 1). Differential friction, necessary to produce propulsion, is obtained by mass effect (mass of the elongated body sections vs. mass of the expanded body sections). On the other hand, worms with a limited number of segments must exploit special structures (legs, anchor points) to obtain differential friction, and thus locomotion.

For example, the fishing worm of Fig. 2 - consisting of only 10 segments - enhances his peristaltic propulsion by exploiting small active structures located on the back side which can extend and retract by increasing friction onto the substrate.

Experimental observations demonstrate that earthworms have different speeds 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.

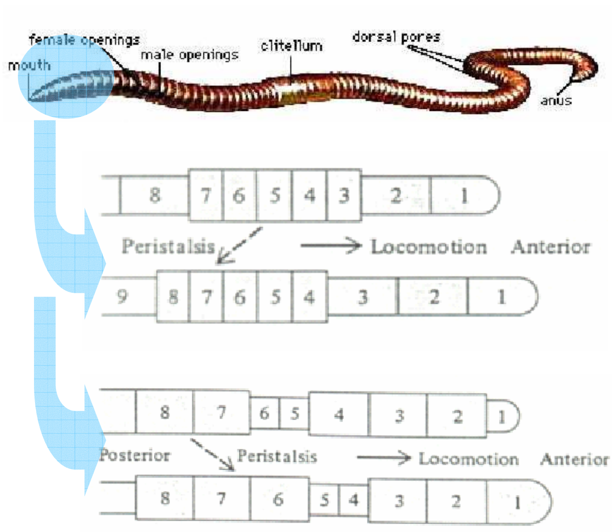

Fig. 1. Locomotion scheme of an earthworm with many segments.

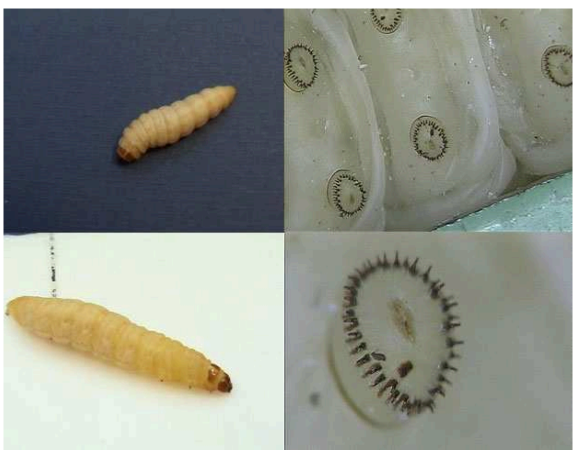

Fig. 2. Fishing worm with 10 segments and hooking structures on the back side.

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 biomimetic Robotic Earthworm

After optimizing the module parameters [9], the crucial problem in the design of an artificial earthworm is 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) [10], [11], [12]. SMA wires with 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 burrowing and locomotion ability depends on setae geometry and friction properties rather than module force). The design of the artificial module is shown in Fig. 3.

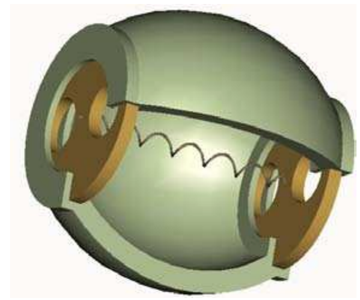

Fig. 3. Earthworm module.

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.

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 (finite element analysis) 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.

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.

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.

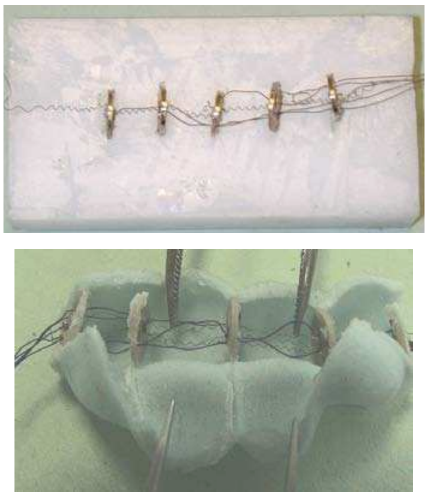

Fig. 4. Earthworm skeleton.

Fig. 4 shows the internal SMA mechanism of the earthworm. The silicone shell is obtained by moulding. A stereolithography mould has been fabricated in Nylon.

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.

In order to enable the robot moving on a flat surface (as it will be detailed in the following), directional metal micro-legs have been fabricated by wire Electro-Discharge Machining. The micro-legs are hook-shaped and their typical structure is illustrated in Fig. 5.

A prototype featuring the directional micro-legs has been developed, as illustrated in Fig. 6. Each segment has been provided with 4 micro-legs, and all legs have been manually glued under microscope along the same direction to the external shell of the earthworm. As the legs are oriented in the opposite direction respect to the locomotion direction, they perform the same task of the setae of biological worms which provide points of friction with the substrate. In fact the contracting or non-contracting segments of the robot produce small friction, whereas the directional micro-legs supply differential friction conditions along a preferential direction, significantly contributing to the advancement of the robotic earthworm.

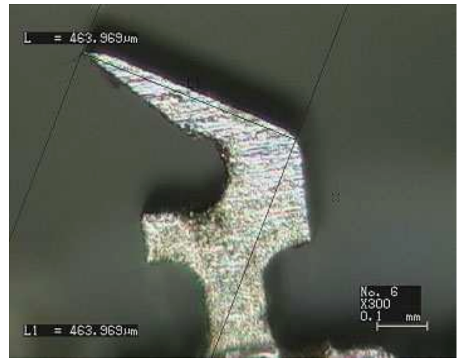

Fig. 5. The directional micro-leg.

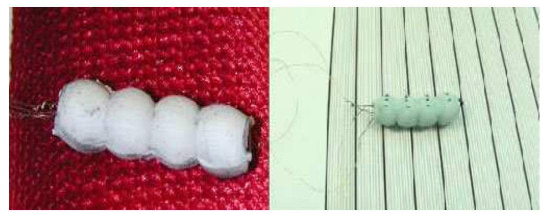

Fig. 6. Prototypes: without micro-legs(left), with micro-legs.

V. Locomotion Experiments

The advancement 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 without legs 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 propelling the robot onto a directional surface, such as a velvet surface, thus producing differential friction during elongation and retraction phases of the segment; the second one consists of the fabrication of tiny directional legs, thus mimicking the biological setae, as reported above.

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.

Table I shows the experimental parameters used to characterize the earthworm locomotion of microrobots without micro-legs on the shaped substrate and the final results.

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 Ω.

TABLE I. EARTHWORM VELOCITY (WITHOUT LEGS)

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

Table II shows the experimental parameters used to characterize the earthworm locomotion with micro-legs on flat surfaces (Fig. 7), and the final results. The prototype earthworm has still 4 segments and 1 spring for segment, but it uses 75 μm in diameter wire, rather than 100 μm in diameter wire as in the previous prototypes. This increases the working frequency - because of shorten cooling time of the spring - thus increasing robot speed.

TABLE II. EARTHWORM VELOCITY (WITH LEGS)

Frequency (mHz)	Current peak duration (ms)	Current (mA)	Energy for module (J)	Velocity on flat surface (mm/s)	Velocity on sloped surface (40°) (mm/s)
330	320	400	0.15	0.7	0.45
530	260	350	0.096	2	1.43
600	130	350	0.05	2.5	1.25

Fig. 7. The earthworm with micro-legs moving on flat surface.

Locomotion performance with anchoring legs is effective also on Teflon substrate (Fig. 8). In this case, the maximum speed goes down to 1.4 mm/s under the maximum operation frequency (0.6 Hz).

The maximum locomotion force has been measured for both prototypes during the climbing of the earthworm onto a sloping surface, by avoiding that the tail interfered with the robot motion (Fig. 9 and Fig. 10). For the earthworm without micro-legs, 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°).

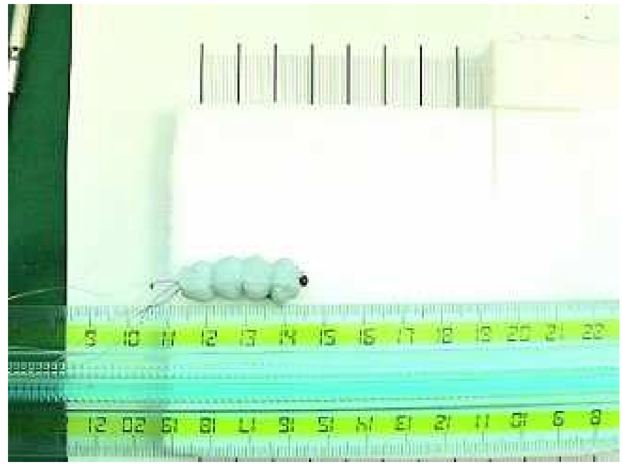

Fig. 8. The earthworm with micro-legs moving on Teflon substrate.

By considering the mass of the earthworm, which is 1.4 g, a maximum locomotion force of 5.8 mN has been derived.

Fig. 9. The earthworm climbing the sloping velvet surface.

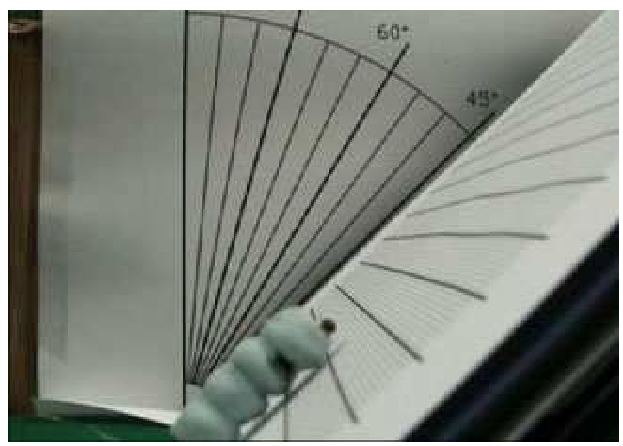

Fig.10. The earthworm with micro-legs climbing on sloping surface.

Setting the locomotion parameters as in the last line of the Table II, the earthworm can climb a sloping substrate up to the maximum angle of 45°. By considering a robot mass of 1.2 g, we derive a maximum propulsion force of 8.3 mN.

VI. CONCLUSIONS AND FUTURE WORK

The SMA actuated artificial earthworm has demonstrated encouraging results in terms of speed and activation frequency.

Conferring the robot steering ability is a key problem currently being addressed. Modules with 3 independent springs have been designed: 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.

An additional improvement consists of inserting the micro-legs directly during the moulding of the external body, in order to partially embed them and reduce fabrication steps.

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.

REFERENCES

[1] R. J. Full, “Invertebrate locomotor systems”, in *Handbook of Physiology*, Section 13: Comparative Physiology, Vol. II, W. H. Dantzler, Ed. New York, NY: Oxford University Press, 1997.

[2] S. Hirose, “Snake-Like Locomotors and Manipulators” *Biologically Inspired Robots*, NewYork: Oxford. University Press, 1993.

[3] H. R: Choi, S. M. Ryew, K.M. Jung, H.M. Kim, J. W. Jeon, J. D. Nam, R. Maeda, K. Tanie, “Microrobot actuated by soft actuators based on dielectric elastomer”, *Proc. of IEEE/RSJ International Conference on Intelligent Robots and System*, Vol. 2, p. 1730-1735, 2002.

[4] E. V. Mangan, D. A. Kingsley, R. D. Quinn, H. J. Chiel, “Development of a peristaltic endoscope”, *Proc. of IEEE International Conference on Robotics and Automation*, Vol. 1, p. 347-352, 2002.

[5] L. Phee, D. Accoto, A. Menciassi, C. Stefanini, M.C. Carrozza, P. Dario, “Analysis and Development of Locomotion Devices for the Gastrointestinal Tract”, *IEEE Trans. Biomed. Eng.*, June 2002.

[6] A. Menciassi, P. Dario “Bio-inspired solutions for locomotion in the gastrointestinal tract: backgroud and perspectives”, *Phil. Trans. R. Soc. Lond. A* 361, p. 2287-2298, 2003.

[7] J. Gray, “Studies in animal locomotion: The kinetics of locomotion of Nereis diversicolor”, *The Journal of Experimental Biology*, p. 9-17, 1939.

[8] K. J. Quillin, “Kinematic scaling of locomotion by hydrostatic animals: ontogeny of peristaltic crawling by the earthworm lumbricus terrestris”, *The Journal of Experimental Biology*, p. 661–674, 1999.

[9] A. Menciassi, S. Gorini, G. Pernorio, P. Dario, “A SMA Artificial Earthworm”, *Proc. of IEEE 2004 International Conference on Robotics and Automation*, April 26-May 1, 2004.

[10] M. Hollerbach, I. W. Hunter, J. Ballantyne, "A Comparative Analysis of Actuator Technologies for Robotics.", in *Robotics Review 2*, MIT Press, Edited by Khatib, Craig and Lozano-Perez, 1991.

[11] K. Ikuta, M. Tsukamoto, S. Hirose, “Mathematical model and experimental verification of shape memory alloy for designing microactuators”, *Proc. of the IEEE Micro Electro Mechanical Systems International Conference*, p. 103-108, 1991.

[12] J. Van Humbeeck, D. Reynaerts, J. Peirs, “New opportunities for shape memory alloys in the field of actuators, biomedical engineering and smart materials”, *Materials Technology*, Elsevier, Vol. 11(2), p. 55-61, 1996.