A biomimetic sensor for a crawling minirobot

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Abstract

This paper presents the development of a biomimetic sensor, with the ability to imitate exteroceptor and proprioceptor functions of invertebrates, such as earthworms. A polyvinylidene fluoride (PVDF) film is selected as the sensing element because it is flexible, highly sensitive and easy to be integrated in different shapes. Perforated PVDF strips are embedded in a segmented silicone shell of a crawling earthworm minirobot with the ability to elongate and contract, thanks to a smart configuration of shape memory alloy actuators. A 4-segment minirobot with a sensorised skin has been fabricated. Experiments on separate sensorised silicone segments and also on the sensorised minirobot show that the biomimetic PVDF-based sensors can detect both the external contact and the internal actions, thus imitating the exteroceptive and proprioceptive sensing capabilities of real earthworms.

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1. Introduction

An increasing amount of research and literature exists on the understanding and replication of motion abilities of animals which propel them efficiently in different environments where normal propulsion systems (e.g. wheels) fail [1,12,13,16,21,35, 41]. The typical applications of this research range from rescue robotics, to industrial inspection and to the field of medical endoscopy [7,8,23,27,32,39,40].

P. Dario et al. developed robots for semiautonomous colonoscopy by taking inspiration from the inchworm locomotion of some insects and parasites (e.g. leeches) [28, 30,33]. R. Vaidyanathan et al. developed three segments hydrostatic robots which locomote under water and they also gave a kinematic model for multi-segments hydraulic skeleton robots [42]. J. Steigenberger developed a mathematical model of a worm segment following the paradigm of the earthworm [38]. Grundfest et al. developed a robotic endoscopy system consisting of traction segments and actuation segments which could provide inchworm-like or snake-like locomotion [18]. H. Kimura and S. Hirose developed a snake-like robot – called Genbu 3 – with passive rigid joints and touch sensors for detecting the posture in order to establish the most appropriate control method [25]. J. Ayers et al. built biomimetic water current receptors, statocysts, vestibular receptors and other neuromorphic sensors which encode specific sensory modalities (gravity, water current). These informations evoke different control methods for lamprey robots and lobster robots [2–4]. A.J. Ijspeert et al. developed neural locomotion controllers inspired by a biological connectionist model of a lamprey’s CPG (Central Pattern Generator). Experiments showed that the simulated lamprey was able to cross a speed barrier when endowed with sensory feedback and it was not able to do the same without sensory feedback [22].

The most suitable machine for locomotion in hostile and tortuous terrains (such as the small cavities of the human body and – in particular – the intestine) should be an “environment sensitive” and “soft” device, which should be able to autonomously manage the navigation at a low level, while the high level control is performed externally by the operator. For this reason, the robotic replication of a crawling earthworm should consider not only locomotion mechanisms,
but also perception systems and neural control, together with the enabling technologies to implement such a type of “imitation”.

One of the main problems determining the failure of early approaches to machine intelligence was probably the assumption that intelligence is essentially abstract thinking, and that therefore human intelligence could be developed by powerful computers capable of high speed calculations and logic (sequential) reasoning [6]. As the animal world vividly demonstrates, the reality is that intelligence evolves and is built primary on the availability and processing of sensory information. Recent research on intelligent machines and systems assumes that sensors are key components for obtaining adaptive and intelligent behaviour [11]. Thus, it is very important to develop proper sensors not only for on-bench applications, but also for intimate integration with miniaturized mobile structures, which are able to perceive both the surrounding environment and the internal status of these mobile structures.

This paper focuses on the realization of biomimetic sensory abilities for a crawling earthworm minirobot, which has been designed to replicate the locomotion mechanism of living earthworms in order to address useful applications wherever locomotion in unstructured environments is required.

Based on these considerations, Section 2 deals with the fundamental biological inspiration in sensor development; Section 3 illustrates the design of the proposed exteroceptive and proprioceptive biomimetic sensor; Section 4 shows the fabrication of the sensor by exploiting PVDF technologies; instruments, methods and experiments are described in Sections 5 and 6. Finally, Sections 7 and 8 illustrate test results and conclusions, respectively.

2. Biological inspiration

All living beings possess sensors and sensor processing abilities, by means of which they perceive and respond to the environment within and outside of themselves. For all animals, sensing is critical for the guidance of their particular behaviour, and for regulating metabolic and reproductive processes. The evolutionary process over hundreds of millions of years has led to a fascinating number and variety of sensory systems. The animal kingdom offers many solutions for a wealth of sensory problems.

Complex sensing organs, such as palps, antennae and cirri, which are present also in simple paddleworms (i.e. errant polychaete) are absent in most crawling earthworms (i.e. oligochaete). However, single receptor cells or small sens- ing organs are found distributed in abundance throughout the skin of earthworms. The majority of these sensing systems are mechanoreceptors that allow the worm to immediately respond to external contact and other mechanical stimuli [26]. There is good physiological evidence for the existence of proprioceptors to detect hydrostatic pressure and stretching of longitudinal muscles in earthworms [31]. However, so far no matching anatomical structures have been clearly identified.

One interesting sensory system is present in all primarily aquatic vertebrates, like cyclostomes (e.g. lampreys, eels), fish, and amphibians; they have in their outer skin (epidermis) special mechanoreceptors called lateral line organs able to detect the motion of surrounding water. The name “lateral line” originates from the line running from head to tail, in which the neuromasts (a core of mechanosensory hair cell) are located at regular intervals [17,43].

Another interesting inspiration comes from human muscle structure: Golgi tendon organs (one of the musculotendinous receptors) and muscle spindles. The Golgi tendon organs are located between the muscle and its tendon, and they are sensitive detectors of tension in distinct, localized regions of their host muscles. Muscle spindles are located throughout the muscle between parallel muscle fibres. Here they undergo the same length change as the rest of the muscle. They are sensitive to the muscle fibre’s length and detect the stretch of their adjacent muscle fibres. Their functional substructure provides constant monitoring and regulation of sensory-motor functions that enable appropriate body movement.

3. Design of the biomimetic sensor

Highly flexible and compliant sensing elements are necessary to develop a biomimetic sensing system of an artificial earthworm. In fact, the working principle of the earthworm is based on peristaltic contractions and elongations of its compliant segmented body.

Some examples can be found in the literature of sensitive flexible layers and sensor arrays to provide tactile information when embedded in robotic artifacts. On the other hand, the engineering process of these sensing principles is often very complex and this difficulty hampers and limits a real use of these sensing systems in robots. Flexible piezoresistive devices whose sensing layer is carbon or silver-impregnated rubber have been developed [19,20]. These devices measure resistance changes between the conductive rubber and the electrode. The creep, hysteresis and crosstalk due to the hardness of the silicone rubber edge are major drawbacks. Furthermore, the viscoelastic property of the silicone rubber layer limits the dynamic range, and the electrical connections with conductive rubber are sources of noise. Recently, an electronic artificial skin with large area plastic film and mechanical flexibility based on organic transistor has been developed by Someya et al. [36,37]. This technology is promising to develop animal-like sensitive skin, but till now it is still a long way from really practical applications due to low sensitivity, low response frequency, problems with humidity, short lifetime even sealed with compliant plastic films, and relatively high drive voltage. Another kind of flexible sensing system was developed by integrating a silicone MEMS device in polyimide substrate [24, 45]. These silicon based systems are reliable and have good resolution thanks to the well assessed micro-fabrication processing, but the brittle character of silicon may still cause some failures and it is also not capable of sustaining large deformation and sudden impacting. The fabrication procedure is obviously complicated and high cost, not suited for batch
production. One different polyimide flexible tactile sensor was developed by J. Engel et al. with a metal membrane embedded in polyimide: it is robust and low cost, but the effective gauge factor is very low [14].

Between other materials with sensing ability, PVDF film fits the needs very appropriately. PVDF is a semi-crystalline polymer with approximately 50%-65% crystallinity. It can be prepared in thin films ranging between 6 µm and 2 mm in thickness and it can be made fairly flexible. Consequently, the PVDF can be easily formed into complex and uneven surfaces. Due to its flexibility, excellent sensitivity and dynamic response, PVDF films are extensively used for contact detection and mimicking human tactile sensing [10,15,34].

Finally, for intimately integrating the sensing element with the mobile structure (which will be described in the next subsection), easy fabrication and robust behaviour are the main structural requirements. In fact, the objective of the authors is to develop relatively simple sensors able to detect the external contact signals and also to feel the internal actions like real animal exteroceptors and proprioceptors.

The artificial earthworm is only an interesting possible embodiment for the PVDF-based sensitive skin. What is most important is to have developed a soft silicone sensitive skin that can solve other various problems (e.g. biomimetic skin of soft-body robots). Based on this consideration, the innovation of this paper is the development of a versatile PVDF-based sensor for exteroceptive and proprioceptive applications, by building up a method which allows using in a reliable way sensing films which are not normally usable in a straightforward way.

3.1. The segmented structure of crawling earthworm minirobot

The artificial earthworm consists of several independent segments. Each segment is 1 cm in diameter and approximately 1 cm in length. SMA springs link two brass discs that are connected to electrical wires (Fig. 2(a)). The antagonistic structure for the shape memory alloy (SMA) spring consists of a silicone shell. When current is established between the two discs, the SMA spring is heated for the Joule effect and contracts (austenitic phase), thus bending the silicone shell. Once the current is removed, the SMA spring turns to the plastic phase (martensitic phase at low rigidity), and the silicone shell can recover its original shape, thus pulling the SMA springs to their original length. Consequently, the silicone shell serves as an artificial earthworm skin and passive longitudinal muscle. Based on finite element simulations of the segment, the thickness of the silicone shell has been selected to be 0.8 mm [28,29].

The earthworm-like robot is composed by four segments, each one with a SMA spring actuator. As shown in Fig. 2(b) the electronic board, containing a Microchip PIC12F625 microcontroller and a driver circuit for the SMA spring, is located in one of the discs which close the segment, while the other disc is used just to connect SMA wires to a voltage supply. The robot locomotion is inspired by oligochaeta worms which travel exploiting the generation of a longitudinal wave along their body. In order to replicate that behaviour, the robot segments are activated by contracting the SMA spring in each segment sequentially from the head to the tail. The activation command to each segment is sent from the head microcontroller, which works as a master module, to the other microcontrollers, which work as slave modules since they are usually in stand-by state just waiting for an activation command. Communication between segments is based on a serial protocol, where a single byte, containing information about the active segment, is sent from the master to the slaves.

3.2. Biomimetic design

Earthworms possess sense organs distributed throughout the body, as described in Section 2, so that they can quickly respond to external contacts and also detect the longitudinal muscle stretch and hydrostatic pressure. Similarly, all crawling minirobot segments must possess the sensibility to external and internal stimuli. It is important to find a proper way to integrate PVDF films into each minirobot segment and finally to endow the minirobot with the ability of exteroception and proprioception like its animal counterpart. The authors have developed two prototypes of a sensorised minirobot segment: one with 2 PVDF strips on the left and right sides of the segment and one with 4 strips on the left, right, up and down sides.

There are different solutions to integrate PVDF films into silicone shells: e.g. gluing the film to the inner or outer surface of the silicone shell, or embedding the film directly into the silicone shell.

Gluing is the simplest solution, but it involves some drawbacks. First of all, from the practical viewpoint, it is difficult to deal with the electrode wires of the PVDF sensors if gluing the strips to the inner surface of the silicone shell. Moreover, there are sensor perturbations caused by the heating and cooling of the SMA because of the pyroelectric effect. Finally, another important problem is related to the interface between the PVDF film and the silicone shell, which can become quite stiff thus changing the elastic property of the silicone shell itself. Gluing the PVDF film to the outer surface of the silicone shell reduces problems of heating and wiring, but the film is afflicted by high mechanical noise – such as sounds – because of the PVDF strip’s high sensitivity. Based on the above considerations, an embedding process has been selected (as shown in Fig. 2(b)).

The PVDF we used forms a crystal symmetry as described in [44]. The piezoelectric coefficient for this form can be written as

\[
d_{ij} = \begin{bmatrix}
0 & 0 & 0 & 0 & d_{15} & 0 \\
0 & 0 & 0 & d_{34} & 0 & 0 \\
d_{31} & d_{32} & d_{33} & 0 & 0 & 0
\end{bmatrix}.
\]

When a traction force is applied along directions 1 or 2, or a compression force is applied along direction 3 (see Fig. 3), the output charge is expressed by:

\[
\frac{Q}{A} = d_{3n} \sigma_n
\]

where:
Fig. 1. (a) Lateral line system on a zebra fish: the green dots are neuromasts located along this line. (b) Scheme of a neuromast.

\( n(1, 2, 3) \): Mechanical stress axis direction
\( \sigma_n \): Stress applied in relevant direction
\( d_{3n} \): Piezoelectric coefficient
\( A \): Electrode area
\( Q \): Charge generated by stress.

In voltage mode the equation is changed to

\[ V_o = g_{3n} \sigma_n t. \]

Here the piezoelectric coefficient \( d_{3n} \) is replaced by \( g_{3n} \) and
\( t \): PVDF film thickness
\( V_o \): Voltage output.

In our application the contribution of output is mainly related to the length direction stress, due to the sensor configuration. Even in the normal external contact situation, the contact force to the silicone shell will be changed to stretch the shell due to the compliance of the silicone membrane property. Therefore, the force caused by external contact and internal elongation/contraction motion acts on the thickness of the cross-section of the PVDF strip. When the PVDF strip is being stretched by the load, the equation regulating the process is

\[ V_o = g_{31} \frac{F}{w t} = \frac{F}{w} \]

where
\( V_o \): PVDF voltage output
\( F \): Force acting on the PVDF film
\( w \): Width of PVDF film
\( t \): Thickness of PVDF film
\( g_{31} \): Piezoelectric coefficient.

From the equation above, it is clear that PVDF strip sensitivity will increase by reducing the strip width. For this reason a narrow thin PVDF strip was selected to mimic the exteroceptive function of the lateral line system.

In an animal lateral line system (Fig. 1), each neuromast is an independent local sensory center. The PVDF strips applied on each segment of the minirobot constitute a lateral line sensory system in order to endow the earthworm crawling minirobot with exteroception ability.
Fig. 4. The perforated PVDF and the cross section view of PVDF in silicone sandwich configuration: the fluid silicone entering the holes, forming good fixation.

The embedded PVDF strip should undergo the same length change together with the silicone shell when it elongates and contracts, as do the Golgi tendon organ and muscle spindles during muscle contraction/elongation. Preliminary experiments showed that fixation is weak when embedding a narrow thin PVDF strip in the silicone shell because of the electrode surface’s smoothness, which brings a limited friction, so slight pulling forces can slide the strip out of the silicone shell. If the PVDF strip is perforated at regular intervals, the fluid silicone can go through the holes during the embedding procedure thus fixing the PVDF strip robustly in the silicone shell after molding. Another advantage is that the same PVDF strip achieved higher sensitivity after being perforated.

In order to avoid dramatic changes of the silicone shell mechanical properties, 28 µm thick PVDF film has been selected. For easily fixing the electric wires to the two sides of the PVDF strip, the authors chose a width of 2 mm strip to cover the length of the silicone shell. By considering a segment length of about 10 mm, the silicone shell arch is about 12 mm. Consequently, the final size of the embedded PVDF strips is 12 mm × 2 mm × 28 µm, with three holes (the diameter is about 1 mm) manually machined along the shell length (the center to center distance between holes is 4 mm). The holes are cut out with a hollow steel cylinder (1 mm in diameter) whose tip edge is sharpened. The silicone shell and the perforated PVDF strip form a sandwich configuration as illustrated in Fig. 4.

Fig. 5. (a) Mould for fabrication and integration of the PVDF sensor, (b) inner and outer electrode resistances measurements.

4. Fabrication of the PVDF sensor and integration in the segmented minirobot

4.1. One-step molding fabrication

An acrylic resin mould (consisting of a core and an external mould), made by rapid prototyping technology, is used to fabricate the artificial earthworm silicone shell and the sensor lodgments. The external mould consists of four reassembly parts to allow the fabrication of four PVDF sensors in the same segment, with PVDF strips located on the left, right, top and bottom for detecting the external contact coming from different directions (Fig. 5(a)).

The external mould and the core are designed to leave a 0.8 mm gap for lodging the silicone and PVDF strips. The PVDF film is covered by a thin layer of metal film on each side as the electrode. Before and after embedding the PVDF strips, the resistance of the metal film on each side was measured as shown in Fig. 5(b). Longer (more than 12 mm) PVDF strips were used for easier measuring after embedding. One of the ends of the silicone shell was cut off after performing the measurement; another end is left for wire connecting.

The stress when moulding and peeling off the silicone shell can cause damage to the PVDF electrode. In fact, the original resistance of the electrode for the PVDF strip is about 20 Ω; after integration the resistance is generally more than 600 Ω. In
Table 1
Resistance values of inner and outer electrodes

<table>
<thead>
<tr>
<th>Four sensors in one shell</th>
<th>Inner resistance</th>
<th>Outer resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor 1</td>
<td>40 ± 0.5 (\Omega)</td>
<td>35 ± 0.5 (\Omega)</td>
</tr>
<tr>
<td>Sensor 2</td>
<td>115 ± 0.5 (\Omega)</td>
<td>82 ± 0.5 (\Omega)</td>
</tr>
<tr>
<td>Sensor 3</td>
<td>18 ± 0.5 (\Omega)</td>
<td>33 ± 0.5 (\Omega)</td>
</tr>
<tr>
<td>Sensor 4</td>
<td>40 ± 0.5 (\Omega)</td>
<td>18 ± 0.5 (\Omega)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Two sensors in one shell</th>
<th>Inner resistance</th>
<th>Outer resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor 1</td>
<td>21 ± 0.5 (\Omega)</td>
<td>29 ± 0.5 (\Omega)</td>
</tr>
<tr>
<td>Sensor 2</td>
<td>18 ± 0.5 (\Omega)</td>
<td>21 ± 0.5 (\Omega)</td>
</tr>
</tbody>
</table>

some cases the electrode is completely destroyed. After many trials, the authors adjusted the fabrication procedure as follows:

- Clean the external mould and the core with cleaning water and dry.
- Align the perforated PVDF strip in the proper position and fix one end of the strip on the reassembly mould part with tape.
- Shape the PVDF strips in the mould for half an hour.
- Pour the fluid silicone into the four mould parts; let the PVDF strip touch the silicone and stick on it; add additional silicone on the PVDF strips.
- Assemble the four parts with the core to form the entire structure, pressing slightly.
- Fix the entire structure with two clamps: one gives pressure from top to bottom, the other from left to right; relieve the fixing tape; gradually tighten the two clamps.
- Cure in air for 2–3 h; disassemble the external mould and peel off the silicone shell from the core.

Table 1 gives the resistances of electrodes of PVDF sensors in one silicone shell by following the above procedure. The damage caused by the molding and peeling off stress has been successfully reduced in the configuration with two PVDF sensors. During peeling off the silicone shell from the core, in 2-strips configuration, fingers can avoid pushing the silicone part under which the PVDF strip is embedded, while in 4-strips configuration it cannot be avoided because of lack of space. Consequently, another method was considered; the silicone shell was longitudinally cut and peeled off, so pressure on 3 of the 4 PVDF strips is avoided. That is why the resistance of one strip changed distinctly in 4-strips configuration. For this reason the authors carried out the experiments on the 2-strip prototype fabricated with the above procedure. Prototypes developed by following the procedure are shown in Fig. 6(a).

4.2. Moulding–embedding–remoulding (MER) fabrication

By exploiting the above fabrication procedure, two-strip segments were successful developed. On the other hand, one major limit of that procedure is that a few PVDF strips can be integrated into the silicone shell. Based on this consideration, a new fabrication procedure which evolved from shape deposition manufacturing (SDM) [5] was developed. The MER fabrication procedure is showed in the following diagram.
impedance. Since both amplifier stages are supplied by a single 5 V stabilized voltage, all signals are translated to a 2.5 V bias in order to have a full system dynamic exploitation.

Several tests showed that the described circuit design was affected by 50 Hz noise due to electromagnetical interference; for this reason we selected to insert a notch filter stage, with a centre frequency of 50 Hz, in cascade to the differential amplifier. We generated this type of filter by using a single supply 5th order switched-capacitor filter with a Butterworth response (Maxim MAX7409), configured as explained in [9]. The use of a switched-capacitor filter allows us to accurately set the notch centre frequency by changing an external capacitor in order to reach the desired value.

5.2. Testing bench

The testing bench for characterizing the PVDF biomimetic sensor has to fulfil the following requirements:

• It must be capable of generating a controlled vertical displacement on the sensorised silicone shell with different frequencies and amplitudes. This is requested in order to mimic the function of contraction and elongation of the biomimetic segment.
• The pressure force that is applied to the PVDF sensor must be measured on line, in order to study the sensor response to different loads.
• It must acquire at least two signals: one from PVDF circuitry and one from load sensor. The acquisition frequency should be freely selectable and acquired data must be stored in a file.

We chose to use a data acquisition board (National Instruments DAQcard 6062) for both data acquisition and tip actuation control. This board has 16 analog input channels and 2 analog outputs; both with 12 bits digital conversion resolution, a ±10 V of input/output range, maximum sampling rates of 500 kS/s for inputs and of 850 kS/s for outputs; furthermore it can be interfaced through a PCI-MCIA port to a PC. Another important advantage of this device is the possibility to realize a human–machine interface (HMI) by using a simple Labview 7 (National Instruments) virtual instrument.

In order to generate a periodic tip movement, we connected a plastic structure to a woofer membrane, able to oscillate driven with a sinusoidal voltage; between the plastic structure and the tip, which pushes the PVDF film, we inserted a load cell (Sensotec 11/1127-02) in order to measure the applied pressure. The woofer membrane is actuated through an analog output of the DAQ board followed by a driver circuit, based on a power operational amplifier (National Semiconductors LM675) in a non-inverting configuration. The woofer is fixed to a metallic bracket in a vertical position as shown in Fig. 9. The height of the woofer can be finely regulated to select the right distance between the tip and the PVDF strip integrated in the segment.

The HMI allows controlling all parameters related to the tip actuation, i.e. sine wave frequency and amplitude, and to data acquisition, i.e. sampling frequencies, acquisition time and saving filename.
6. Testing methods

During normal working of the mobile segment, the embedded PVDF strips integrated into the segment are subjected to two types of stimuli: the external contact pressure on the surface where the artificial earthworm segment is moving, and the contraction/elongation of the segment due to the internal actuator. Consequently, we set up two different experimental protocols to test the effects of external contact and contraction/elongation of the segment. In all tests, for both protocols, we acquired data by using a sampling frequency of 1 kHz; woofer oscillation frequency and amplitude were selected as described in the following. Since it is necessary to acquire a sufficient number of periods to process each test, acquisition time was set at 30 s for oscillation frequencies larger than 1 Hz and 90 s for those lower than 1 Hz.

All data are saved in text files and then processed by using Matlab 6.5 software (The MathWorks); the processing algorithm includes a 4th order median filtering of samples and a low pass filtering using a 2nd order Butterworth filter with a cut-off frequency equal to ten times the tip oscillation frequency.

6.1. Detection of external contact

The configuration of the system in order to test sensor behaviour when an external force is applied to the robot external surface is shown in Fig. 10.

In order to evaluate the frequency response of the PVDF sensor for the external stimulation we set up the following procedure: the same load (about 30 mN) is applied to the tip at different frequencies (from 0.2 to 20 Hz); then the mean value of sensor peak to peak voltage outputs – at all sinusoidal periods – is calculated. Before this operation we needed to develop a segmentation algorithm for the PVDF signal in order to evaluate the waveform in each period; for this reason we chose the load cell signal as reference for segmentation, which is both stable and reliable. Consequently it was straightforward to identify a threshold value to select start and end instants of a single period.

Once the stimulation frequency for which the sensor has the larger peak to peak output was identified, we performed a new experimental test in order to evaluate PVDF full dynamics: we fixed the tip oscillation frequency at the value found before and then we changed the oscillation amplitude from 20 to 160 mN, with 6 mN step. Then the peak to peak values from the PVDF
sensor were measured as described above, thus obtaining a clear indication about load response of the sensor.

6.2. Detection of segment contraction/elongation

The setup used to test the PVDF response when contraction/elongation is applied to the robot segment is illustrated in Fig. 11.

One side of the segment was fixed to a bottom support, while the other side was glued to a shaft which replaced the tip described above, thus imitating the actuation of the SMA springs described in Section 3 in a reliable way. Since the objective of the test is also to measure the sensor response for large oscillation frequencies, we chose this setup instead of directly using the SMA actuation. The experimental procedure performed in this case was similar to that one described in the section above: different oscillation frequencies were applied to the sensor at fixed amplitude, corresponding to about 2 mm of displacement between contraction length and elongation length. No varying load trials were performed in this session, because the typical segment contraction/elongation is fixed and defined by SMA actuation limits.

Since in this case the periodicity of the PVDF signals was not clear as in previous experiments, we did not analyze the peak to peak values, but the whole morphology of the signal for each frequency: after segmentation with the load cell signal, we evaluated the mean wave of PVDF signals for each period, and compared them for all frequencies.

6.3. Detection of external contact during segment contraction/elongation

As the final test of the characterization procedure, we analyzed the possibility of distinguishing the external contact stimulation during normal segment operation, i.e. contraction/elongation. The capability to detect external contacts is very interesting for robot propulsion, because it can be used as a feedback signal to control the robot actuation and to define a particular motion strategy.

By using the testing system setup as described in the previous section, we acquired data from sensors for an interval of 10 s. During this time interval, at a random instant an external contact was manually applied to the segment. The woofer oscillation amplitude for this experimental session was about 2 mm as in the above section. Two oscillation frequencies (0.5 and 0.6 Hz) were selected in order to replicate typical operating frequencies of SMA actuators.

As will be illustrated in the next section, the results of these last experiments highlighted a difficulty in distinguishing the two stimuli on PVDF sensors in the time domain; thus we evaluated the power spectrum for this signal and compared it with the power spectrum of the tests made at the same frequencies in the previous experimental task without the external contact.

7. Results

7.1. Detection of external contact

Three examples of PVDF processed signals at different stimulation frequencies are shown in Fig. 12. In each interval a maximum and minimum are clearly visible; thus peak to peak values are measured between these two points. Since the higher peak to peak mean value of PVDF signals is at a frequency of 11 Hz (Fig. 13(a)) we selected this frequency to test load response of the sensor. The relationship between load cell output and PVDF signal is reported in Fig. 13(b).

7.2. Detection of segment contraction/elongation

The typical waveforms for some frequency tests performed for this characterization are shown in Fig. 14. The red line corresponds to the load cell output for each sinusoidal period: when it goes down, we have contraction of the segment, while when it goes up we have elongation. We divided the PVDF signals into three groups on the basis of their morphology respect to load cell behaviour: in the first group (from 0.2 to 1 Hz), during the contraction phase, we have a small increase in PVDF signal and then a small decrease during the elongation phase. In the second group (from 2 to 4 Hz) there is a change in the signal trend, since it decreases during the contraction phase and increases during the elongation phase. Finally in the third group (from 5 to 20 Hz) the signal trends as in the first group. In the first group PVDF signals at 0.5 and 0.6 Hz are of particular interest since these two frequencies are those selected in order to replicate typical contraction/elongation frequencies of the segment (Fig. 15).

7.3. Detection of contact in presence of segment contraction/elongation

From the PVDF signals in the time domain it is not clear if an external contact was applied during contraction/elongation, so this brought us to consider the evaluation of power spectra to distinguish between the two cases.

The calculated power spectra of PVDF signals during the segment contraction/elongation, evaluated from data collected in the previous experimental task (at 0.5 and 0.6 Hz oscillation frequencies), are shown in Fig. 16. At the same frequencies, adding a manually applied external contact as illustrated in
Section 6.3, we had power spectra as shown in Fig. 17. A difference between these last spectra and those shown in the previous figures is clearly identifiable at low frequencies, differentiating the two cases.

7.4. Measurement of the minirobot sensitivity with SMA actuation of the segments

It is critical to validate the segment’s sensitivity under real working conditions. Therefore the experiments on single SMA activated segments and on a minirobot with 4 segments were purposely carried out.

The segmented minirobot was sequentially actuated by heating the SMA spring (SMA wire diameter 100 µm), thus contracting and then dissipating and relaxing, which imitates the real earthworm locomotion. The silicone segment can achieve about 2 mm contraction after 150 ms heating of the SMA spring and then recovers to its original length by relaxing. The actuation procedure is arranged like this: first each segment is heated for 150 ms one by one, and then it is given a 1.5 s dissipating time for all the segments. Thus the total cycling time is 2.1 s for the 4-segment minirobot. Thus the working frequency for the minirobot is about 476.19 mHz. But frequency contraction/elongation for the single segment is higher because length recovery time for the segment is less than the temperature recovery time for the SMA wire.

7.4.1. Single segment experiment

One end of the 4-sensor segment was fixed to one plate while the other was kept free. The segment was activated by the SMA spring, and the outputs of four sensors were acquired by the
Fig. 14. Contraction/elongation experiments: PVDF and load cell mean periodical waveforms at different stimulation frequencies: (a) 0.2 Hz, (b) 1 Hz, (c) 2 Hz, (d) 4 Hz, (e) 5 Hz and (f) 20 Hz. All curves are processed in order to reduce single wave samples to 80 points and then to achieve comparable waveforms at different frequencies.

7.4.2. Minirobot experiments

Fig. 19(a) showed the output from the last segment of the 4-segment minirobot, during sensitivity experiments. Although the segment’s actuation signals appeared normal, there are

DAQ system. The results are shown in Fig. 18, and the different colors represent different sensor signals. Regular pulse signals perfectly followed the SMA pulse actuation in time. During the actuation time, the external contacts were manually added on the parts of silicone shell under which are the embedded PVDF strips. These contact signals are clearly showed in the figure and easily recognized (indicated with red circles). The outputs of the sensors which were impacted, apparently gave comparably large responses.
some small pulses (3 pluses, indicated in red circles) which regularly occurred in advance of the last segment actuation. After checking the time intervals, we realized they might be caused by the neighboring segment’s actuation. In order to make sure, we took off one segment from the minirobot and the results are shown in Fig. 19(b). In this case just 2 small pulses are present. So it is clear that the developed biomimetic sensors can also feel the neighboring segment’s actuation status.

During the minirobot actuation the external contacts were manually added. The external contact signals are also clearly shown in the figure (Fig. 19(c)).

Thus, the developed sensing system is capable to detect both the external contact (exteroception) and the elongation/contraction (proprioception) both on a single segment and on the minirobot level.

8. Conclusions and future work

In this paper we presented a biomimetic sensor based on PVDF film and integrated into the skin of a crawling earthworm robot. This sensor has been conceived for detecting two types of stimuli on the robot segments: the external contact on the earthworm robot skin and the segment contraction/elongation during peristaltic propulsion.

PVDF films have the advantage of high flexibility, ease of integration into mobile structures, and good sensitivity to stress. The experiments performed to test the sensor response to external contact stimulations show a high reliability of the system, which basically consists of a PVDF film embedded in the silicone skin through an ad hoc fabrication procedure. Up to 20 Hz each single contact period on the surface is clearly identifiable. The PVDF load response, illustrated in Fig. 13(b), shows a saturation of the sensor output at about 80 mN. This is acceptable for our applications, since during robot normal dragging, external forces on the single segment can be assumed to be less than that value.

Some difficulties have been encountered to distinguish PVDF signals during contraction/elongation peristaltic motion in the first prototypes, fabricated by a simple moulding process. Furthermore some dynamics can be observed in the waveforms.
at low frequencies; on the other hand a more stable periodic trend is visible at increasing frequencies (up to 20 Hz). It is interesting to evaluate signal waveform differences in three frequency ranges. In the first range (from 0.2 to 1 Hz), during the contraction phase, we have a small increase in PVDF signal to which a small decrease during the elongation phase corresponds. In the second range (from 2 to 4 Hz) there is a change in signal trend, since it decreases during the contraction phase and increases during the elongation phase. In the last range (from 5 to 20 Hz) we have again a behaviour similar to the first range. This effect is probably due to the capability of PVDF to strictly follow tip motion at high frequencies.

Looking at the power spectra of PVDF signals for 0.5 and 0.6 Hz of contraction/elongation oscillations, the stimulation frequencies appear very clearly (rather than in the time domain, where the periodic behaviour is very noisy). Some small spectrum components at frequencies different from the excitation one could be due to resonance effects on the PVDF sensor and also to mechanical inertia of the testing structure.

An interesting result is the comparison of spectra with and without external contacts: when an external contact is added to the normal peristaltic motion, a significant component at low frequency appears, only related to the contact presence. Through a frequency analysis, it is easy to distinguish the normal contraction/elongation effect on PVDF from external contacts.

By improving the fabrication procedure for the multi-sensor silicone segments (i.e. MER procedure), we succeeded in obtaining more reliable sensors. The experiments on improved biomimetic sensors showed much better sensitivity on the contraction/elongation: single actuation cycles of segment are easily identifiable also in the time domain. The contact signal on a single segment and on the minirobot during the SMA actuation period can be easily identified. Furthermore, the developed biomimetic sensor system can also feel the neighboring segment’s actuation status.

The above results demonstrate that this activity can be a first step towards the implementation of a biomimetic sensing
system with the function of exteroceptor and proprioceptor, i.e. able to detect external contact signals and also to feel internal actions.

In living creatures the locomotion system is endowed with structural, actuation and sensing functions, which are fused and harmonized together. Intimately integrating sensing elements into actuation structures gives the possibility to build a real smart intelligent structure, useful for distributed local controlling. For this reason the next research activity will deal with controlling a minirobot by exploiting the developed sensing system and trying to imitate the “actuation–sensing–actuation” animal-like behaviour.

Furthermore, in the next work we will try to implement a system directly on board the earthworm segment and to use different types of sensors, together with PVDF, to implement a complete sensory system in order to collect different information about the robot’s state.

Hopefully, the sensorised crawling earthworm minirobot will constitute a platform for improving the knowledge of mechanisms which regulate motion and perception abilities of lower animal forms.

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