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Using a Soft Growing Robot as a Sensor Delivery System in Remote Environments: A Practical Case Study

Stanislao Grazioso
Department of Industrial Engineering
University of Naples Federico II
Naples, Italy
stanislao.grazioso@unina.it

Annarita Tedesco
IMS Laboratory
University of Bordeaux
Bordeaux, France
annarita.tedesco@ims-bordeaux.fr

Roberto Sabella
Herobots S.R.L.
Naples, Italy
technical@herobots.eu

Salvatore Fusco
Herobots S.R.L.
Naples, Italy
technical@herobots.eu

Mario Selvaggio
Dep. of Elect. Eng. and Inf. Tech.
Univ. of Naples Federico II
Naples, Italy
mario.selvaggio@unina.it

Luigi Duraccio
Dept. of Elect. and Telecomm.
Polytechnic University of Turin
Turin, Italy
luigi.duraccio@polito.it

Egidio De Benedetto
Dep. of Elect. Eng. and Inf. Tech.
University of Naples Federico II
Naples, Italy
egidio.debenedetto@unina.it

Antonio Lanzotti
Department of Industrial Engineering
Univ. of Naples Federico II
Naples, Italy
antonio.lanzotti@unina.it

Leopoldo Angrisani
Dep. of Elect. Eng. and Inf. Tech.
University of Naples Federico II
Naples, Italy
leopoldo.angrisani@unina.it

***Abstract*—Soft continuum robots are a new class of robotic devices, which are very promising for enabling measurement applications especially in remote, difficult-to-reach environments. In this work, we propose the use of a particular soft robot, which is able to evert and steer from the tip, as a sensor delivery system. The measurement system consists of two major sections: *i*) the robotic platform for movement purposes; and *ii*) the sensing part (i.e., a sensor attached to its tip to enable the measurement). As a case study of the use of the soft-growing robot as a sensor-delivery system, the transportation of a wired thermocouple towards a remote hot source was considered. The preliminary results anticipate the suitability of soft continuum robotic platforms for remote applications in confined and constrained environments.**

***Index Terms*—Soft Robotics; Soft Growing Robots; Remote Measurements; Remote monitoring; Sensors.**

I. INTRODUCTION

The *Industry 4.0* revolution is characterized by a fusion of technologies that is blurring the lines between the physical, digital, and biological spheres [1]. In particular, information technologies such as the Internet of Things [2], brain-computer interface [3], artificial intelligence [4], [5], machine learning [6], cloud computing [7], additive manufacturing [8], wearable sensors [9]–[11], as well as augmented, virtual, and mixed realities [12], [13] are fostering the digital transformation in industry.

The contribution of this technology becomes particularly relevant, for example, in contexts where a support for remote measurement task in confined and constrained environments is required [14]. For the sake of example, in [15] a fiber-based projection-imaging system was proposed for shape measurement in confined space. The system relied on the flexibility of imaging filter to perform measurement in special scenarios that are difficult for conventional experimental setups. In [16] a sensor constituted by an electronic endoscope and a pair of mirrors was designed to implement three-dimensional measurement in confined space. Finally, in [17], an ultrasonic waveguide-based temperature sensor was used for confined space measurements.

In fact, this task represents a challenging technological problem that is difficult to be solved with standard robotic technologies. This is the case not only in industrial applications, but also in different application scenarios where the site to be explored is difficult to reach and/or with unknown characteristics (e.g., for exploring in archaeological sites or collapsed buildings).

Another interesting approach is represented by the adoption of *soft continuum robots*, namely robots composed of a continuously deformable mechanical structures [18], [19]. They are ideal candidates for the successful execution of these tasks, due to their possibility to traverse cluttered spaces and conform their shape to nonlinear paths, while guaranteeing a compliant and safe interaction with the surrounding environment. In the literature, there are several examples of soft continuum robots for remote measurement applications, in both industrial and medical scenarios, as reported in [20].

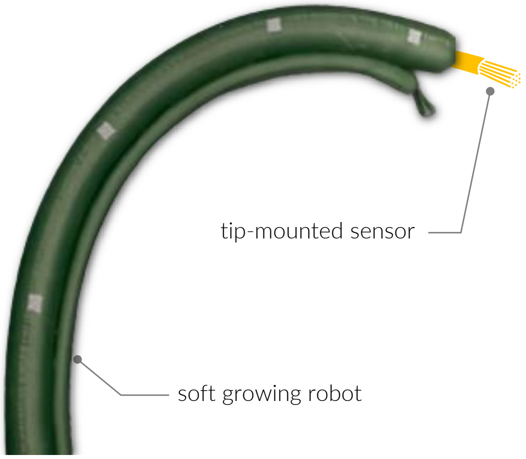


Fig. 1. Soft growing robot with a tip–mounted sensor as a sensor delivery system in confined environments.

Soft continuum robots are particularly appealing in the case of delivery sensors in long–to–be–reached remote targets, accessible only by small-scaled entrance sections. Applications include reaching long–distance targets within known environments, as within the assembly phase of large structures (as in airplane manufacturing) or collecting data in unstructured environments, as example for scientific studies or explorations. For these cases, a recent design solution referred to as *soft growing robots* can be of particular interest [21], with multiple benefits in remote measurement and monitoring applications [22], [23]. Soft growing robots take inspiration from the growth process of plants and vines [24]. Apart from being inherently soft, another great advantage is that they can navigate without sliding through constrained environments [25]. In practical applications, this capability may also be used, for example, for accommodating elongated sensing elements that must be placed underground [26]–[32].

In this work, we use a soft growing robot as a system to deliver sensors in confined and constrained spaces. As a proof of concept, a wired temperature sensor is connected to the tip of the soft growing robot in such a way that both the wire of the sensor and the body of the robot evert simultaneously, till reaching the remote measurement target (see Fig. 1).

The paper is organized as follows. In Section II-A we describe the soft growing robotic system, while in Section II-A we describe the performed experiments and the results of the work, with conclusions given in Section IV.

II. MATERIALS AND METHODS

A. The Soft Growing Robot

The soft growing robot considered in this work is made up of an everting backbone and two fabric pneumatic artificial muscles (fPAM) glued to its diametrically opposite sides. The backbone is inverted such that when pressurized it pulls new material out from its tip causing the robot body to extend by growing (see Fig. 2). When pressurized, the laterally attached fPAM contracts and cause a shortening of the backbone side, thus making this to deform and thus steer its tip (see Fig. 3). The material of the backbone and the fPAM is a double side silicon-coated ripstop nylon, which guarantees negligible friction during the eversion process. The rip-stop pattern of the material is simply a plain weave with thicker, reinforcing strands at regular intervals in both the warp and weft direction. The key to the operation of the presented fPAM is fabric bias. Indeed, the fabric is inextensible along the major thread lines, but is fairly elastic along the fabric bias at a 45° angle to these threads. This means that a tube of bias-cut fabric will be elastic, while a tube with a straight or cross grain cut will not. As a result, when the tube is pressurized it expands radially while contracting lengthwise. When this tube is attached to a backbone, it causes bending motion to the overall system [33].

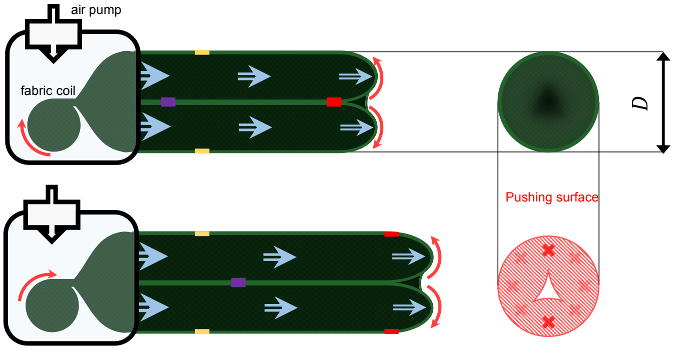


Fig. 2. Eversion mechanism of the soft growing robot.

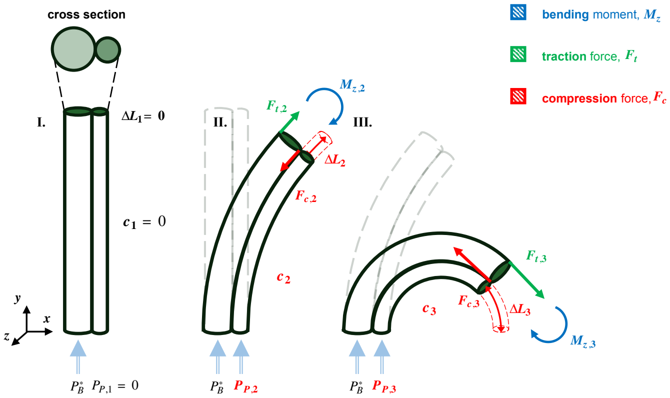


Fig. 3. Bending motion of the soft growing robot caused by a fPAM laterally attached to the backbone.

An important feature of this kind of system is that it is possible to attach at its tip a tethered sensor, in such a way that the eversion of the robot's body and of the sensor's cable acts simultaneously. Another option is to design ad–hoc magnetic caps to be placed at the tip of the robot, to allow the mounting of sensor systems that in this case should be wireless.

B. Experimental Setup and Sensing Task

As a case study, we considered a thermocouple wire directly attached to the tip of the soft growing robot.

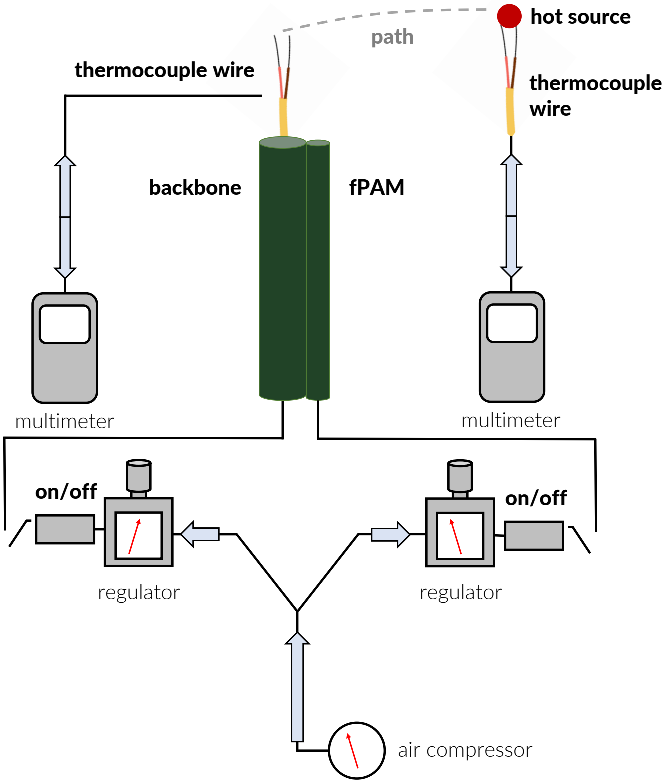


Fig. 4. Sketch of the experimental setup used for considered case study.

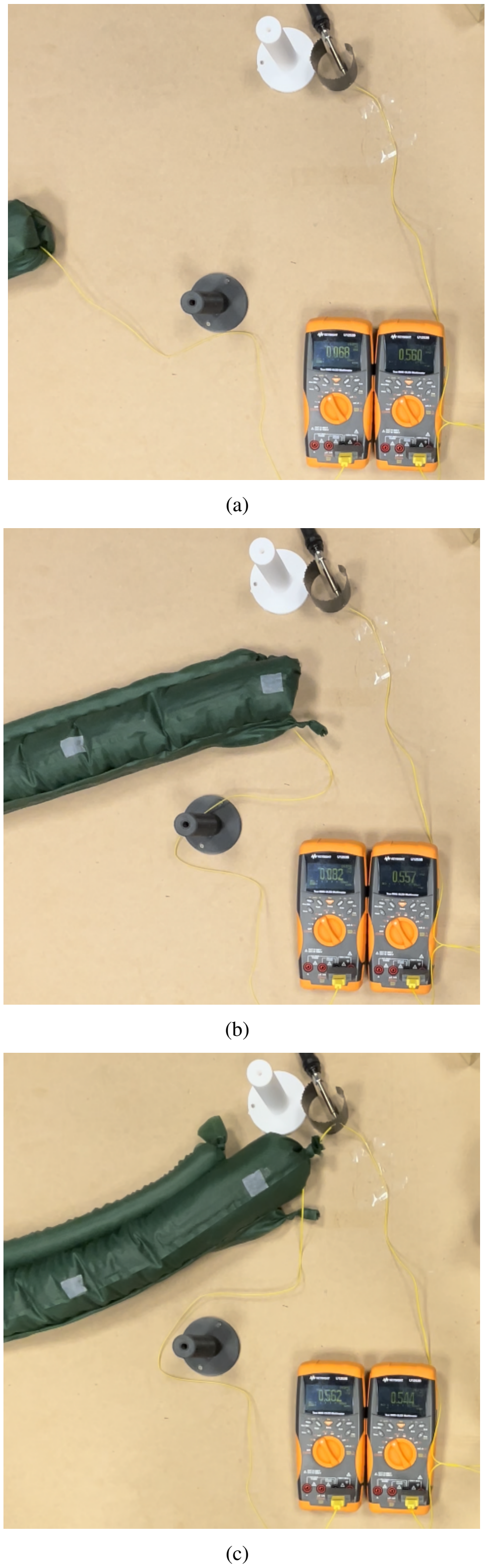
The task considered in this work consists of actuating the soft growing robot with a tip–mounted thermocouple until reaching a *target location* represented as a hot source, and here collecting the temperature measurement.
The experimental setup is illustrated in Fig. 4. It includes the following elements:

- A hot source at a temperature T_{nom} (assumed as free of uncertainty contributions).
- A custom-built soft growing robot with a backbone and a laterally attached fPAM.
- Two type K thermocouple wires (*U1180A*, Agilent Technologies, Santa Clara, CA, USA), one attached to the robot and one attached to the hot source.
- Two digital multimeters (*U1253B*, Keysight Technologies, Santa Rosa, CA, USA) connected to the thermocouple wires for the temperature measurements.

One of the thermocouple wire is preliminarily attached to the tip of the robot in the ineverted configuration. A second thermocouple is attached at the target location: this acts as a reference for the temperature measurement T_{ref}.

III. RESULTS AND DISCUSSION

Figure 5 shows a series of snapshots of the sensor delivery system which is moving towards the *target location*. The yellow cables are the thermocouple wires, one being connected to the robot and one being connected directly to the hot source. As aforementioned, during the movement, the thermocouple


(a)

(b)

(c)

Fig. 5. Snapshots of the experimental test at different time instants while the robot was everting: $t = 0$ s (a), $t = 12$ s (b), and $t = 36$ s (c).

TABLE I
TEMPERATURE MEASUREMENT AT $t = 36\ s$.

T_{nom} (°C)	T_{ref} (°C)	T_{meas} (°C)
50.0 ± 0.0	49.5 ± 1.1	49.4 ± 1.1

wire everts together with the robot's body. Fig. 5(a) shows the beginning of the experiment ($t = 0$ s). Then, the robot everts to reach the target location, at $t = 12$ s. Fig. 5(b) shows the robot while it is everting toward the target location. Finally, Fig. 5(c) shows the robot when it has reached the target location at $t = 36$ s. It can be noticed that when the robot reaches the target location, the two output from the multimeters T_{meas} and T_{ref} are comparable with each other as shown in Table I, where also the type-B standard uncertainty is reported.

This simple task is just a proof of concept for use cases related to the delivery of sensors in remote locations. For the sake of example, further applications can involve (i) the real-time monitoring of multiple measurement points, or (ii) the extraction of a spatial temperature profile from a starting point to an end point, by means of the adoption of wireless sensors attached to the tip of the robot.

IV. CONCLUSION

In this paper, a soft growing robot was used as a sensor delivery system. More specifically, we have developed a measurement setup involving a self-everting and self-steering robotic device, equipped with a wired sensor at its tip, in this case a type K thermocouple. The main result of the work is that the sensor's wire is capable of everting together with the robot, providing a reliable temperature measurement.

Future works will consider the use of non-contact IR temperature sensors that can be mounted directly on the tip of the robot and can potentially allow the collection of a temperature map in the remote environment.

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