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Soft Growing Robot to Enable Monitoring Applications in Remote Constrained Environments

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***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 wireless temperature sensor 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; Monitoring systems; 4.0 Era.**

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 and systems [9]–[14], as well as augmented, virtual, and mixed realities [15]–[19] 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 [20]. For the sake of example, in [21] 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 [22] a sensor constituted by an electronic endoscope and a pair of mirrors was designed to implement three-dimensional measurement in confined space. Finally, in [23], 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* (also called *soft growing robots*), namely robots composed of a continuously deformable mechanical structures [24], [25]. 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 [26].

Soft continuum robots are particularly appealing in the case of delivery sensors in long–to–be–reached remote targets,

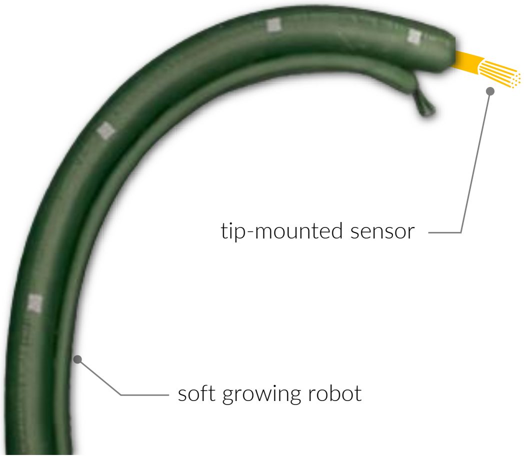

Fig. 1. Soft growing robot with a tip–mounted sensor as a sensor delivery system in confined environments.

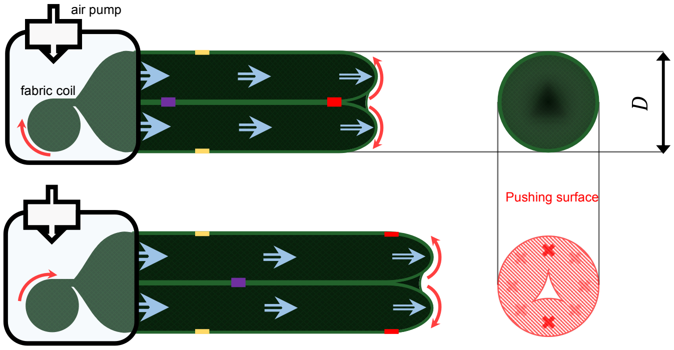

Fig. 2. Eversion mechanism of the soft growing robot.

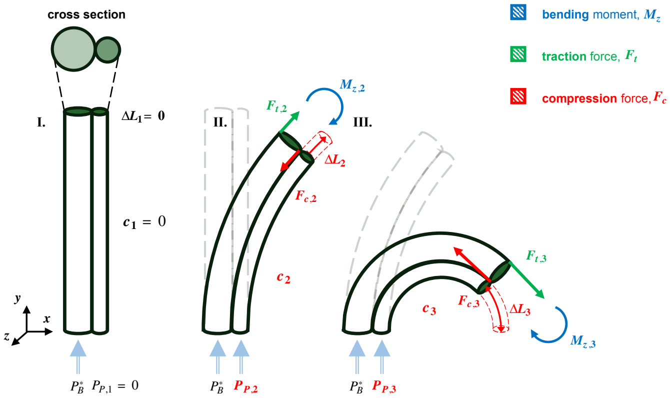

Fig. 3. Bending motion of the soft growing robot caused by a fPAM laterally attached to the backbone.

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 [27], with multiple benefits in remote measurement and monitoring applications [28], [29]. Soft growing robots take inspiration from the growth process of plants and vines [30]. Apart from being inherently soft, another great advantange is that they can navigate without sliding through constrained environments [31].

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 wireless temperature sensor is plugged to the tip of the soft growing robot in such a way that both 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 in Section III 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.

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 wireless environment temperature sensor plugged to the tip of the soft growing robot. The task considered in this work consists of actuating the soft growing robot with the tip–mounted temperature sensor until reaching a *target location*. Therefore, temperature measurements are performed during the entire eversion phase in order

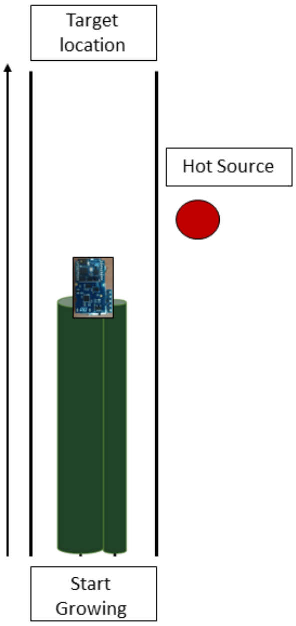

Fig. 4. Sketch of the experimental setup.

to detect the temperature variation of the environment.
To mimic a temperature variation, halfway between the starting point and the target location placed at a distance of 1.5 m from the starting point, the soft growing robot encounters a hot source. The experimental setup is sketched in Fig. 4. It includes the following elements:

- A hot source, namely a heat gun.
- A custom-built soft growing robot with a backbone and a laterally attached fPAM.
- A wireless temperature sensor, namely the *HTS221*, a capacitive digital sensor developed by STMicroelectronics. It is part of the *STLCR01V1 cradle* board, which is connected to the *STLCS01V1 SensorTile* board, in order to send the measurement data to a PC or smartphone over Bluetooth Low Energy protocol (more info at [32]). In Fig. 5, the connection between the sensor board and the soft growing robot is shown.

III. Experimental Results and Discussion

Figure 6 shows a series of snapshots of the sensor delivery system which is moving towards the *target location*. The sensor board is mounted to the tip of the soft growing robot. As aforementioned, during the movement, the board everts together with the robot's body. Fig. 6-a shows the beginning of the experiment. The robot grows at uniform speed until it encounters the hot source. Then, the robot everts until it encounters the hot source (Fig. 6-b). After 10 s, the robot resumes the eversion (once again, at a constant speed) until it reaches the target location ((Fig. 6-c). It can be noticed that the environment temperature measurements are performed during the entire task. Fig. 7 shows the measured temperature values as a function of the time. As visible, when the robot encounters the hot source (red box) the temperature sharply increases. After 10-s measurements, the robot was made resume the eversion until it reaches the target destination (blue box). It can be noticed that, even after the robot everts past the hot source, the measured environment temperature exhibits a slow decrease. This thermal inertia is due to the heating of the sensor board, which required almost 5 minutes to dissipate the heat. This aspect is clearly related to the nature of the sensor; and the performed experiments shows that soft-growing robots have the potential to be employed for monitoring temperature

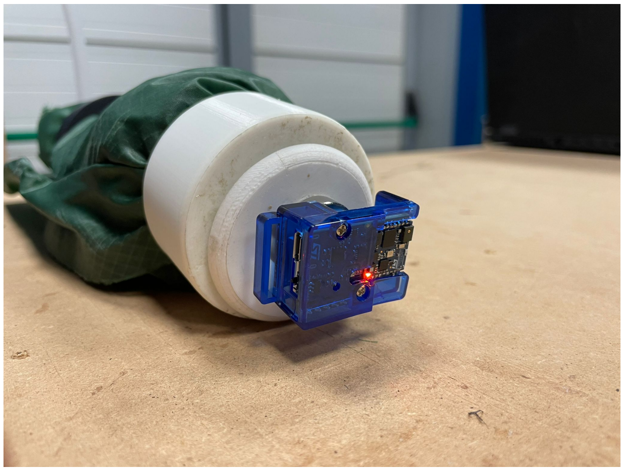

Fig. 5. Detail of the sensor board mounted on the tip of the robot.

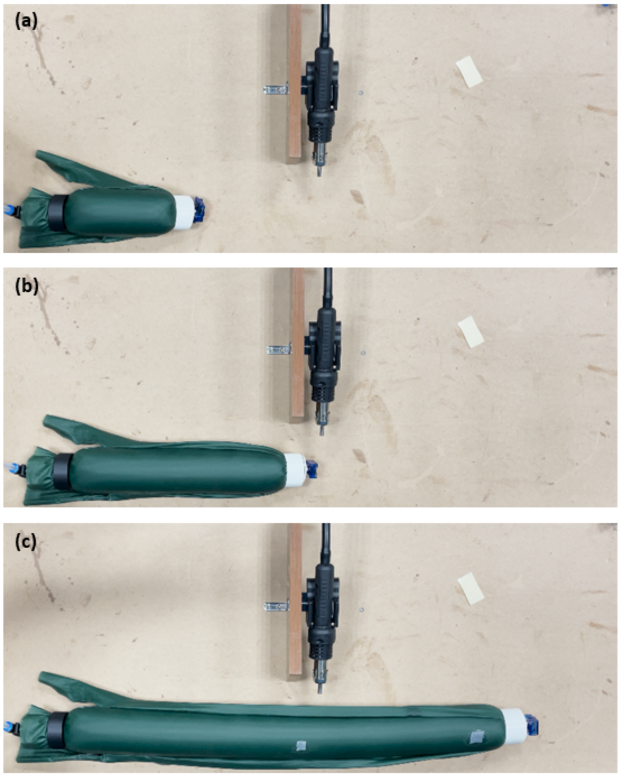

Fig. 6. Snapshots of the experiment: (a) the robot starts growing; (b) the robot reaches the hot source; (c) the robot stops growing.

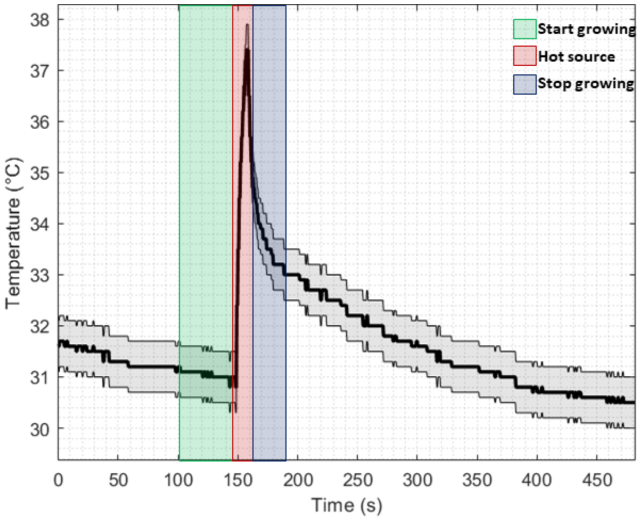

Fig. 7. Measured temperature as a function of time.

profiles (or profiles related to other quantities, depending on the sensor) also in remote, difficult-to-be-accessed areas.

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 wireless temperature sensor at its tip. In this way, the sensor is capable of everting together with the robot, providing temperature measurements during the entire task.

Some thermal inertia was observed due to the heating of the sensor board after it encountered the hot source. Future work will consider the adoption of different wireless temperature sensors in order to allow the collection of a spatially-continuous temperature map in the remote environments. Additionally, future research will be dedicated to (i) the real-time monitoring of multiple measurement points and (ii) to the the extraction of a spatial temperature profile from a starting point to a target point even considering non-linear paths.

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