Design of a Soft Growing Robot as a Practical Example of Cyber–Physical Measurement Systems

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***Abstract*—Measurement and monitoring systems (MMSs) are intrinsically part of 4.0 and, in particular, of cyber-physical systems (CPSs). However, by introducing the 4.0 enabling technologies into MMSs, also the vice versa can be accomplished, and MMSs can evolve into a cyber-physical measurement system (CPMS). Starting from this consideration, in the present work, a preliminary case study of a CPMS is presented: an innovative robotic platform to be used for measurement systems in confined and constrained remote environments. The proposed system is a soft growing robot that includes a robot base, to be placed outside the remote environments, and a robot body that accesses the site through growth. A pneumatic actuation mechanism enables the controllable growth of the system (through lengthening at its tip), as well as its controllable steering. The system can be equipped with sensors to enable remote monitoring tasks, or can be used to transport sensors in remote locations. The ultimate goal is to achieve a self-adapting, fully-autonomous, reliable and safe system for monitoring applications, particularly useful for the remote inspection of unknown and/or constrained environments.**

***Index Terms*—4.0; soft continuum robots; soft growing robots; remote monitoring; monitoring systems; inspection.**

I. Introduction

The 4.0 Era is characterized by an innovative multi–disciplinary approach which addresses technical challenges by seeking transverse solutions to both technological and methodological problems. The most effective expression of the 4.0 paradigm is represented by cyber-physical systems (CPSs), i.e. smart systems that include engineered interacting networks of physical and computational components, able to monitor and control the physical environment [1], [2]. From this definition, it appears that measurement and monitoring systems (MMSs) are essential for the implementation of CPSs. However, MMSs are generally considered as subordinate elements of a CPS: they provide source of information for the CPS (i.e., connection to the physical world) but do not participate in any higher–level actions of the CPS (i.e., conversion, cyber, cognition, configuration) [3]. MMSs are just seen as responsible for sensing the conditions from the physical environment, rather than providers of higher–level intelligent information. However, the suitable adoption of the enabling technologies can reshape the role of MMSs in the 4.0 Era. This requires a fundamental change of perspective, in which the enabling technologies stop being employed as external superstructures for MMSs, and become embedded solutions, intrinsically present in the architecture of the MMS, and fully effective through an adequate metrological configuration. This approach emphasizes the holistic nature of monitoring, and paves the way for *4.0 transition-driven monitoring systems*. Through the wise adoption of the 4.0 enabling technologies, the very definition of MMSs is reshaped as they evolve into self-aware, self-conscious, self-maintained entities, able to generate highly-valued insights, just like CPSs. This means that MMSs can evolve into *cyber-physical measurement systems* (CPMSs), thus becoming a pro-active expression of the 4.0 Era, strengthening not only the role of measurement, but the performance of the overall 4.0 ecosystem.

Starting from these considerations, this work introduces a definition for the CPMSs and present a preliminary case study, i.e. a soft growing robot for measurement and monitoring applications in constrained and confined environments. This

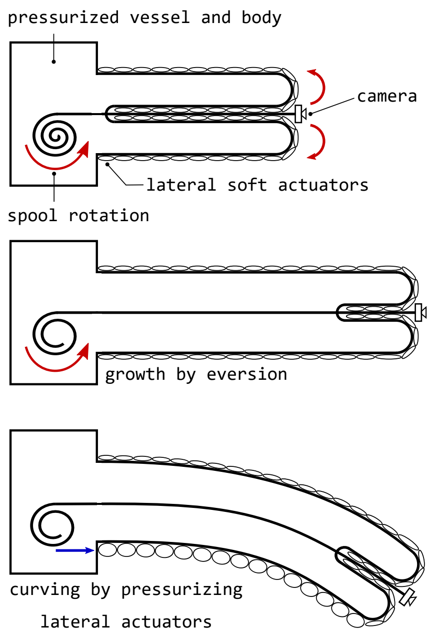

Fig. 1. The concept of growth by eversion of material rolled onto a spool and the concept of curving by pressurization (and thus, contraction) of actuators placed and sealed on the main body.

system is a good example of CPMS for its ability to sense itself within the environment (i.e., *self-awareness*), to adapt itself to the surrounding environment (i.e., *self-configure*), and to navigate autonomously through the inspection site (i.e., *self-predict*). The goal is to show how embedding multiple 4.0 enabling technologies in one measurement and monitoring system represents a promising solution for achieving the CPMS capabilities.

The rest of the paper is organized as follows. In Section II, we present the state-of-the-art of robotic technologies for measurement and monitoring remote applications in difficult–to–reach environments. Then, in Section III we introduce the definition for the CPMSs. Section IV relates to the design of the soft growing robot. Finally, in Section V, conclusions are drawn and the future work is outlined.

II. Background

This section presents a brief overview of robot–assisted measurement and monitoring systems within constrained and confined environments.

As well known, robotic technologies are largely used for carrying out remote measurement tasks, especially in environments that are dangerous or difficult to reach. Nevertheless, there are a number of applications in which traditional robot technologies are not suitable. This occurs, for example, when measurements must be carried out in confined, constrained, or even unknown environments (e.g., exploration of archaeological sites which are often inaccessible and fragile). One technological solution suitable to perform this kind of tasks is represented by soft continuum robots [4], i.e. robots with a continuously deformable mechanical structure, whose design takes inspiration from the principles of shaping, movements, sensing and control of soft biological systems [5]. In the literature, there are several examples of soft continuum robots for remote measurement applications, in different fields: space, airlines, nuclear, marine (inspection and maintenance), medical (minimally invasive surgery) [6].

One limitation of soft continuum robots is their limited workspace, as they usually have a fixed base and a pre–established fixed length; this can be a problem for tasks that require inspection and exploration of large environments. To overcome this issue, soft continuum robots can be endowed with locomotion capabilities, by using tethered/untethered fluidic or cable-driven actuators, taking inspiration from the animal movements (snake, earthworms, caterpillars) [7], [8]. However, this solution requires a relative movement between the robot and the environment, and thus high sliding friction to move, lowering the energy efficiency of the robot. Indeed, a recent design of soft continuum robots achieves enhanced mobility through growth rather than locomotion, taking inspiration from the growing process of plants and vines [9]. These robots, referred to as *soft growing robots*, achieve mobility by everting new material at the tip [10]: this enables lengthening without relative movements between the robot's body and environment. With this solution, the inspection/exploration length of remote environments is therefore limited only by the amount of robot's body material that can be transported on the field, to enable the real tasks. The growing process starts by pressurizing a fluid inside a chamber and by rotating a spool where the robot's main body is rolled; this enables the forward growth of the robot's body through lengthening at the tip. While growing, the robot's body can be curved/steered by pressurizing additional actuators distributed along its body (e.g., pneumatic artificial muscles [11]). The contraction of these additional actuators on one side causes a bending motion along that direction. The growing and curving processes are shown in Fig. 1.

In this work, we develop a design concept of soft growing robot which can be used as preliminary application example of the novel concept of cyber–physical measurement system.

III. Cyber–physical Measurement Systems

The concept of CPMS is built on the 5C architecture, commonly used for CPS (Fig. 2). It is based on the following five levels:

- Connection: layer connected with the physical world where the measurements are collected and the sensing is performed.
- Conversion: layer responsible for the very first processing, to endow the system with self–awareness capabilities (i.e. reconstruction of its internal state).
- Cyber: layer responsible for the development of the digital twin model of the measurement system and for endowing the system with self–compare capabilities (i.e. self–awareness within the network).

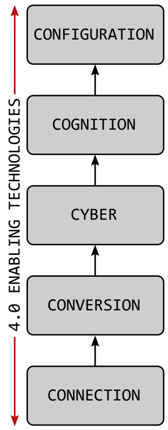

Fig. 2. 5C architecture commonly used for Cyber–Physical Systems.

- Cognition: layer responsible for cognition and reasoning, i.e. high–level models and algorithms to endow the measurement system with decision support capabilities.
- Configuration: starting from the knowledge generated by the cognitive level, this layer generates corrective actions, as adaptation, and reactiveness to the environments.

A CPMS can be defined as a novel form of MMS which, besides the mere data collection from the physical world, is able to provide higher–level information, thanks to the use of suitable models and 4.0 enabling technologies. Similarly to a CPS, a CPMS has knowledge of its state in time and space (*self-awareness*) and with respect to other systems in the network (*self-comparison*); it is capable of enforcing actions for its own maintenance (*self-maintain*), predict its own evolution in time and space (*self-predict*), and adapt to the environment (*self-configure*).

Drawing a comparison with the master-slave architecture, historically MMSs have represented the slaves (mostly dedicated to data collection) of the master (i.e., the CPS itself). By developing CPMS, instead, MMSs becomes CPSs among CPSs; as a result, the current master-slave relationship between MMSs and CPSs eventually turns into a peer-to-peer cooperation.

IV. Case Study: Design of a Soft Growing Robot

This section addresses the design of a soft growing robot, as a preliminary example of development of CPMS. This system is intended to be used for remote measurement applications within confined and constrained environments. First, the design requirements of the system are presented. Then, its major components (i.e. the robotic platform and the electronic control unit) are described in detail. The architecture of the soft growing robotic system is shown in Fig. 3.

A. Requirements

The requirements of the soft growing robot are:

- Access within small-scale cross sections (below 100 mm);
- High inspection/exploration length (up to 10 m) while maintaining portability;
- Growth by eversion using pressurized air with airtight and flexible materials;
- Controllable growth;
- Steering/curving capability; and
- Human situation awareness.

The goal is to develop the first soft growing robot endowed with model–based strategies [12] for planning [13], control and navigation. These requirements give the possibility to develop a general–purpose platform for inspection and exploration uses in a wide range of scenarios.

B. Robotic platform

The robotic platform is mainly constituted by a robot base (where the growing process starts) and the robot body (which accesses the remote environment). The robot base is the container of the unfolded robot and represents the pressurized vessel when the robot is in operation. The main body of the soft growing robot is made of an airtight tube which is flexible but not stretchable. The material should be able to guarantee an almost zero friction in the eversion process while ensuring major durability for field environments. A material that can guarantee these requirements is a double side silicon-coated ripstop nylon. The soft robot body is rolled up and fixed from one hand around a spool inside the pressure vessel: when pressurized, the material everts outside the robot base through an opening. When fully extended the robot body achieves maximum dimensions corresponding to a diameter p of 10 cm and a maximum length l of 10 m. The forward growth is controllable by finding a suitable balance between the desired air pressure to pressurize the vessel and the desired spool rotation, and thus, motor angular velocity along the axis of the spool. For guaranteeing a reversible steering/curving of the robot body, soft pneumatic actuators (made of the same material of the robot's body) are placed along the entire length of the robot: the steering/curving control is guaranteed by a suitable pressurization of these additional actuators, considering models of curvature/deformations of the robot's shape. A camera or a different sensor can be mounted at the tip to perform remote measurement tasks or sensor delivery.

C. Electronic control unit

The electronic control unit is composed by two sub-systems, one for generating the desired air pressure for pressurization of the vessel, one for generating the desired voltage for the DC motor for growth/retraction of the robot body. The pneumatic circuit regulates the air pressure by pulse-width modulation (PWM), which involves the controlled timing of the opening and closing of solenoid valves through a mosfet board, with pressure sensors providing feedback. The pneumatic circuit is an essential component of the robot, as it is responsible for the growth process (one pneumatic tube for the main tube of the robot body) and the possible steering of the robot body (one pneumatic tube for each of the serial soft actuators placed along the robot body).

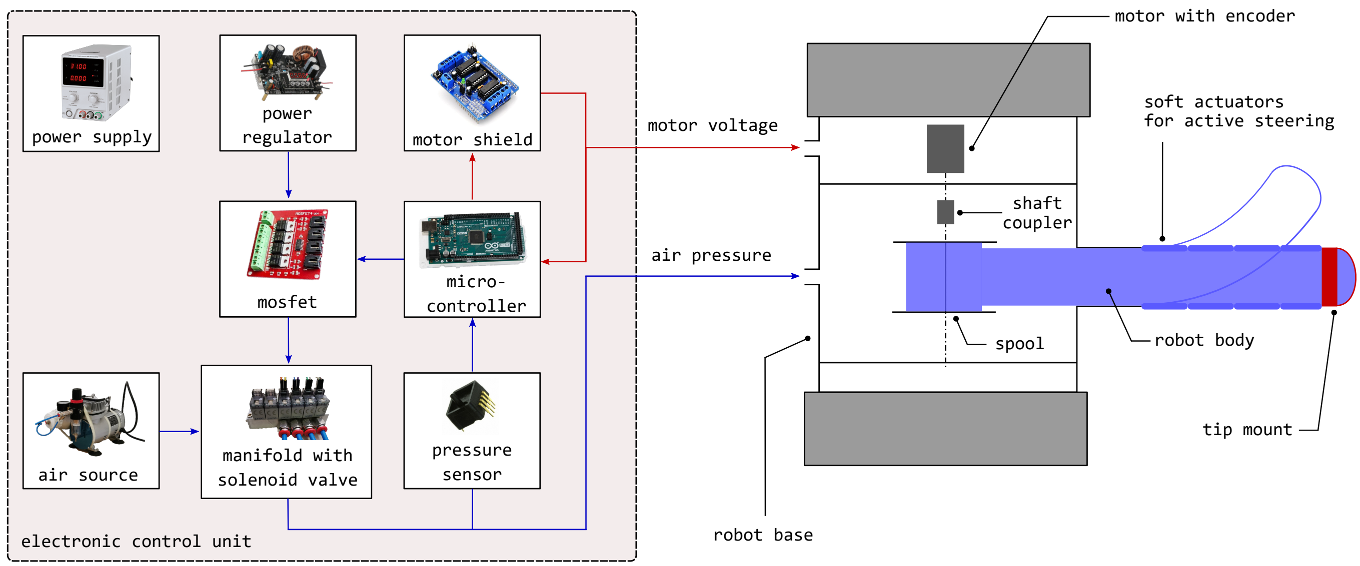

Fig. 3. Architecture of the proposed soft growing robotic system *(dimensions not to scale)*.

V. Conclusion and Future Work

In this work, a definition for CPMS was introduced and a soft growing robot was presented as a case study. A CPMS can be seen as a 4.0–oriented evolution of traditional MMS: thanks to the adoption of 4.0 enabling technologies, a measurement system is not only seen as a system for collecting data, but also for data processing and interpretation as well as an autonomous system that can re–configure its shape to adapt to different measurement tasks. The proposed system is intended to be used for measurement and monitoring applications in constrained and confined environments. It consists of a robotic base, to be placed outside the remote site, and a soft body that accesses the site through growth, with the possibility of controlling length and steering. At the tip of the system, a sensor can be placed to enable remote measurement tasks, or a sensor can be transported, to be delivered when the target is reached.

To achieve a full definition of CPMS, future work will be dedicated to embed additional 4.0 enabling technologies within the CMPS, for endowing monitoring system with autonomous planning/navigation capabilities. Also, effort will be dedicated to motion analysis and control in highly constrained situations. Additionally, a set of practical applications cases will be identified, in order to experiment the system and assess its metrological performance. Finally, suitable sensing technologies and processing strategies will be developed to enhance the metrological performance of the system (e.g., in terms of resolution, reliability and accuracy of interaction with the environment). The ultimate goal is to achieve a self-adapting, fully autonomous system for remote monitoring operations to be used reliably and safely for the inspection of unknown and/or constrained and confined environments.

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