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A Compact Control Unit for a Pneumatic Soft Colonoscope

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***Abstract*—Colorectal cancer is the third most common cause of cancer death worldwide [1]. A regular screening of the asymptomatic population can drastically reduce the cancer mortality. Colonoscopy remains the gold standard procedure, however, it causes pain, discomfort and it is expensive. The procedure is difficult and requires a long training for a colonoscopist to become proficient. A robotic soft colonoscope can provide an alternative solution to the current procedure because of the reduced pressure applied to the colonic wall that can potentially avoid pain and discomfort. The low production cost of soft devices can make the procedure cost effective. The control of a pneumatic system is usually implemented by using off-the shelf components. This typology of design is often bulky, may be noisy, and expensive.**

This work presents a wireless and compact hardware to control a soft pneumatic colonoscope [2]. The hardware includes a low-level PID pressure controllers for each pneumatic chamber, a Bluetooth communication module, and a high-level controller implemented in MATLAB® Simulink to easily test different locomotion strategies.

***Index Terms*—Robotic colonoscopy, soft robotics, colonoscopy, colorectal cancer, medical robotics.**

I. INTRODUCTION

Soft pneumatic robots have had a wide impact in the last decades. This is related to the high compliant mechanical properties and safe interaction with the surrounding environment [3], [4]. Several studies have presented soft pneumatic devices for different applications, e.g., actuators with several degrees of freedoms (DOFs) [5]–[9], planar and spatial manipulator [10], [11], rehabilitation [12], [13], and various other applications [14]. The mechanical performance is often tested by using an open-loop controller. The implementation of a closed-loop controller is mainly implemented by using off-the shelf components. This is related to their high precision, reliability and because they can be integrated with commercially available software, e.g., MATLAB® or LabVIEW, to implement more advanced control strategies. However, this hardware is often bulky and nosy, thus difficult to be used for medical devices in health care centres.

The work presented in this study describes a compact hardware designed to control a soft pneumatic colonoscope [2]. The hardware is a more advanced design of a previous work of the author [15]. The advantages of this design, compared to the previous one, consist of a higher number of controllable chambers, improved firmware to execute up to 6 concurrent PID (proportional integrative derivative) controllers. To simultaneously control a higher number of chambers, 2 modular units have been connected together. Each unit includes the state of the art of miniaturised proportional valve to precisely control the pressure of each chamber connected to miniaturised pressure sensors, and a DSP (digital signal processor).

II. STATE OF THE ART

Soft pneumatic devices can perform dexter movements because of their low mechanical stiffness, passive compliance, and continuous deformation. The hardware control includes sensors, pneumatic valves and air or gas suppliers. Air or gas can be supplied by using several solutions, e.g., a chemical pressure generator [16], or a small tank with high pressurised $C0_2$ gas [17]. However, an external electrical pump is the option that provides a higher flow and higher pressure together with a long and continuous operating time. Efforts to design small hardware are mainly required for untethered robots. For example, a quadruped robot [18] with a length of 65 cm, weight of 5 Kg, is controlled with an on-board control unit and a pneumatic electrical pump. An autonomous soft fish [17] is controlled by using an on-board hardware, a small compressed gas cylinder and propositional on-off valves. A small pneumatic regulator with a distributed control architecture was designed by using small on-off valves and a big-bang control strategy. A Soft Robotic tool-kit [19] is available for educational purpose including drawing and electronic schematic. It uses an Arduino board and a firmware provided to implement the control of solenoid valves. A Wireless Compact Control Unit (WiCCU [15]) was designed to control untethered pneumatic soft robots, with a size of 51x51x23 mm, and a weight of 95 g. It can control up to 3 independent pneumatic chambers. It is composed of 6 miniaturised proportional valves, 3 pressure sensors, a Bluetooth module and a control board with a DSP. One of the leading parameters in the design of a pneumatic hardware is the valve solution. They can be either on-off or proportional. On-off valves have smaller size and are easier to control compared to proportional valves. However, they lack a precise control, essential when a specific pressure profile and high bandwidth are required.

III. METHODS

The design inputs of the proposed hardware control are i) the number of chambers, up to 6, ii) small size, iii) low noise, iv) precise control, and v) easy interface available to connect with external software. The hardware control includes

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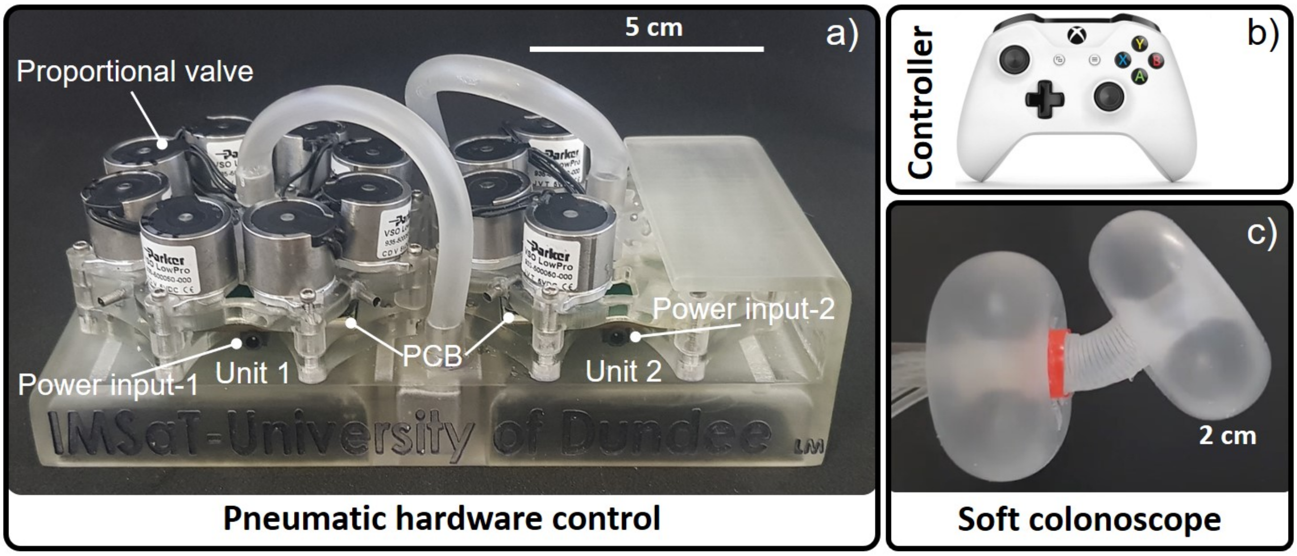

Fig. 1. a) The hardware control including 2 units. Each units includes proportional inlet and outlet valves, a PCB, an independent 5V power input, and a Bluetooth wireless communication. b) X-Box joystick is used as user controller. c) A soft pneumatic colonoscope consisting of a double balloon (2 DOFs) and a central soft pneumatic actuator (3DOFs), for a total 5 DOFs.

2 modular units, each able to control up to 4 pneumatic chambers (Fig. 1). Details of the controller unit are described in the following sections.

A. Control unit

To achieve a precise control of the pressure the hardware uses the state-of-the-art of miniaturised proportional valve Parker VSO® LowPro Miniature Proportional Valves. Each valve weighs 12g, has a size of 20.32x15.87x13.5 mm and a response time of 10ms. The control of the valve can be either voltage or current. To reduce the number of components in the electronic circuit, the input selected for the design was the voltage by using a PWM (pulse width modulation) with a resolution of 12 bits. This input does not directly control the aperture of the nozzle, but the voltage applied to the solenoid to control the displacement of the spool of the valve. This has an hysteresis behaviour that reduces the response time of the system. Each chamber uses an inlet and an outlet valve to increase and decrease the internal air pressure. The inlet valve is connected to the air compressor. The outlet valve is connected to the environment. With this configuration the deflating of the chamber is at natural pressure and slower than the inflation process. The DSP output PWM_i is connected to a half H-bridge with an external voltage of 5V. This is the voltage parameter of the proportional valve, chosen to be powered by using a standard USB supplier. A miniaturised pressure sensor (P_i) for each chamber is soldered to the printed circuit board and connected to a 3D printed manifold. A rubber O-ring secures a sealed connection between the sensor and the manifold. Each chamber uses an inlet and outlet proportional valves connected on top of the manifold. The manifold is 3D printed and connected to the PCB by using 8 screws to avoid air leakage. Communication between the units and an external device (e.g., real-time workstation or a laptop) is implemented by using a Bluetooth module. The firmware of the low-level real-time control is implemented in ”C” code in the DSP. The algorithm implements 3 concurrent process: i) 4 PIDs at 1 Khz; ii) data acquisition of 4 pressure sensors; iii) serial communication and data coding. The overall size of the unit is 143x66x46 mm. An external compressor is used to pressurise the system with a maximal pressure of 200 kPa.

B. Hardware control

The hardware control includes 2 control units connected together. An external air-compressor is connected to the hardware by a 4mm push-fit connector. The air is then split to the 2 control units by using 2 silicon tubes. Each unit has a single power input and an independent Bluetooth connection to increase the bandwidth of the communication. A bridge interface is implemented in Microsoft Visual Studio C++ to exchange data and tune the PID parameters of each control unit. This interface implements a TCP-IP server socket to exchange data with MATLAB® Simulink to implement a high-level control (HLC). The HLC plots the pressure data and connect to a X-Box joystick for user interface. The hardware has been tested with a soft pneumatic inchworm double balloon colonoscope [15] consisting of a distal and proximal balloon (2 DOFs, Degrees of Freedom), connected by a 3 DOFs soft pneumatic actuator, for a total 5 DOFs.

C. Control architecture

The control architecture is shown in Fig. 2, 3. Each control unit has pressure sensors P_i ($i = 1, 2, 3, 4$), a Microchip DSP 16 bits, an RS232 serial port connection to a wireless Bluetooth module. The pressure sensors are from Honeywell NBP series, SMT-PN lead-less, with a maximal pressure of 207

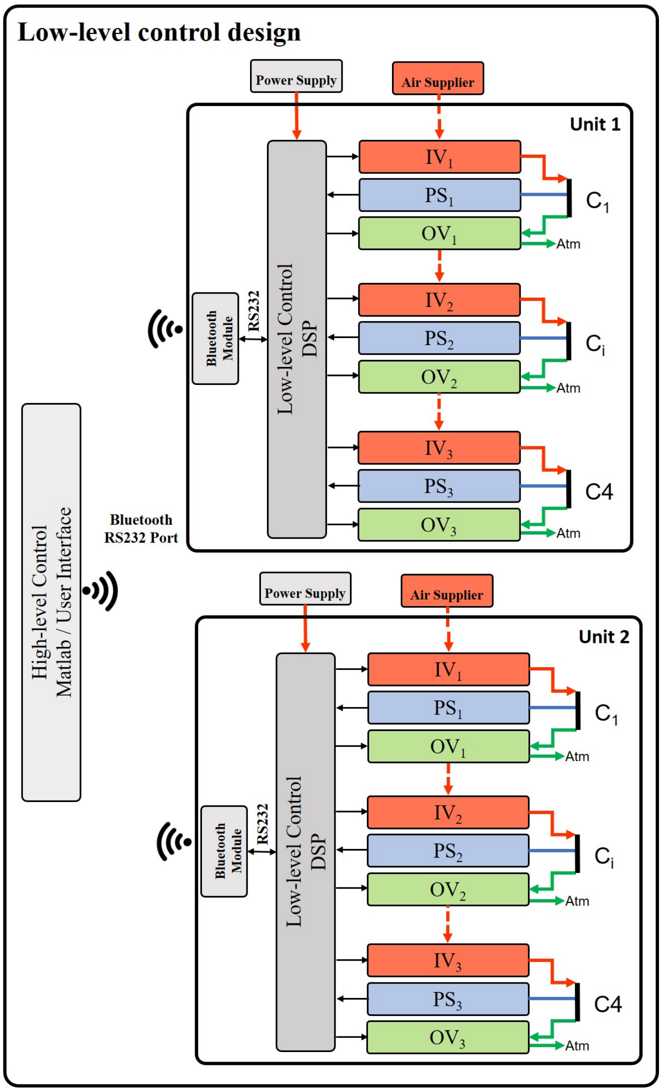

Fig. 2. Control architecture composes of 2 units, a low-level and a high-level control. Each unit has a real-time control implemented in a DSP, input and output valve, pressure sensors and a Bluetooth module. The high-level control is implemented in MATLAB® and exchange data with a bridge software interface by using a TCP/IP protocol.

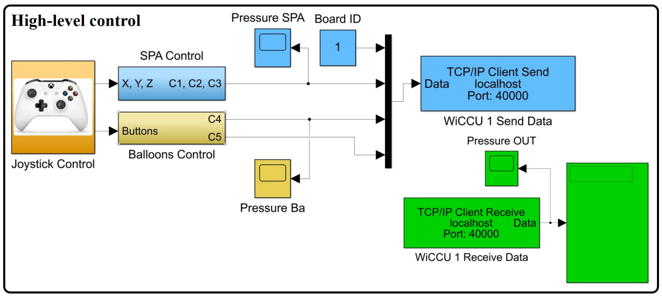

Fig. 3. High-level control. It uses a joystick to control 3 chambers of the soft pneumatic actuator (3 DOFs), for extension along Z axis and rotation around X and Y axes. The inflation and deflation of the balloons is controlled by using 2 more DOFs.

kPa, an error of ±0.25%, and a size of 7.00x7.00x3.84mm. A Wheatstone bridge amplify the pressure output signal and it is then sent to a 12-bit A/D converter of the DSP. A single digital step has a resolution of 80 Pa. The Bluetooth module exchanges data with a bandwidth up to 1 Mbits/s with an external computer. This allows the hardware control to be modular and to connect the 2 units together. Additional units can also be connected to increase the number of pneumatic chambers that can be controlled.

The duty cycle of the PWM has a 12 bits resolution, an input voltage of 5V, and a voltage step of 1.22 mV. The pressure sensors are acquired by using an internal DMA (direct memory access) of the DSP. This reduces the computational burden of the DSP to maximise the bandwidth of the closed loop. The following equations describe the closed-loop control:

$$\begin{aligned} PWM_{d_i} &= K_p e_P + K_i \int_{t-T_0}^{t} e_P dt + K_d \frac{de_P}{dt} \\ e_P &= P_i - P_{ri} \\ &if(P_{ri} > P_{MAXi}) \rightarrow P_{ri} = P_{MAXi} \end{aligned} \tag{1}$$

$$\begin{aligned} & if\ (PWM_{d_i} < 0) \\ & \quad \begin{cases} PWM_{IV_i} = -PWM_{di} + PWM_{do} \\ PWM_{OV_i} = 0 \end{cases} \\ & else\ if\ (PWM_{d_i} > 0) \\ & \quad \begin{cases} PWM_{IV_i} = 0 \\ PWM_{OV_i} = PWM_{di} + PWM_{do} \end{cases} \end{aligned} \tag{2}$$

$$\begin{aligned} PWM_{d_i} &= K_p e_P + K_i \int_{t-T_0}^{t} e_P dt + K_d \frac{de_P}{dt} \\ e_P &= P_i - P_{ri} \end{aligned} \tag{3}$$

The equation 3 describes a PID controller and the equation 2 describes the PWM_{di} to each proportional valve. PWM_{do} is the minimal voltage threshold needed to activate the valve. PWM_{IV} is the input for the inlet valve, and PWM_{OV} the input for the outlet valve. P_{ri} and P_{MAXi} is the reference and maximal pressure for each chamber.

MATLAB® has been used to control and monitor the data, i.e., pressure sensors (P_i) and PWM_{di} outputs. The joystick control provides the pressure for each chamber of the soft pneumatic colonoscope. The 3 DOFs of the soft pneumatic actuator, that connects the 2 balloons, are controlled by the internal pressure and this has a linear proportion to its extension. An operator can control the extension along Z axis and rotation around X and Y axes. A threshold pressure P_{MAXi} is used to avoid the increase of pressure above a dangerous limit.

D. Results

Figure 2 and 3 show the low-level and high-level control. The pneumatic hardware control is a device that facilitates the implementation of locomotion strategies for pneumatic robots. In the presented work the hardware has been used to control a soft pneumatic colonoscope (SPC, Fig. 1-c)) by using an X-Box joystick. The SPC has been tested in a plastic colon phantom showing high dexterity and manoeuvrability. A closed-loop control implements the activation of each balloon to adjust its diameter to the different diameters of the colon. This reduces the pressure against the colonic wall and facilitates the user control of the SPC. The compact design allows the hardware to be portable and easy to install in a healthcare operative theatre. The high-level control can scale down the motion of the user to combine fast locomotion as well as precise control of the tip of the SPC.

E. Discussions and conclusions

This study reports the design of a pneumatic hardware for a precise control of a soft pneumatic colonoscope. The proposed design simplifies the cabling and tubes needed to control a pneumatic device. The modular design can be used to control more DOFs by connecting additional units.

Additional improvements can facilitate the control of a soft robotic colonoscope. This can be done by using additional sensors, such as an IMU (inertial measurement unit), to control the orientation of the soft colonoscope. The advantage of using a TCP/IP communication protocol relies on the possibility to include in the control loop external hardware. For example, a camera vision system that, combined to other sensors, can further improve the locomotion strategies. This can pave the way for an increase in the autonomy levels. The compact design, easy implementation of different locomotion strategies, can facilitate the performance of the procedure by the user. A simplification of the colonoscopy training could potentially allow a nurse under the supervision of a medical doctor to perform the screening with a drastically reduction of costs for healthcare centres and waiting list for patients. In addition, the simple hardware and low-cost production can allow this device to be portable and to be used in countries with low-income economies, potentially increasing the democratisation of healthcare.

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