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A Low-Cost Hybrid Compact Control Hardware for a Soft Colonoscope

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Abstract

Every year about two million new cases of colorectal cancer are diagnosed worldwide, with a mortality close to 50%. Screening and early detection are key to increase the five-year survival rate, which goes above 90% when the cancer is detected at stage 1 and drops below 10% at stage 4. Non-invasive screening, such as FIT (Faecal Immunochemical Test), is adopted in many national bowel screening programs to detect cancer at early stage. Colonoscopy remains the ultimate step to have an optical inspection of the colonic wall and to remove polyps, which may eventually become cancerous. However, this procedure is not well accepted by patients due to pain and discomfort. The pressure of the colonoscope against the colonic wall can damage the mucosa and, in some cases, cause perforation. It is a difficult procedure to learn, and training can take more than 4 years in the UK.

This work presents a hybrid and low-cost control hardware including miniaturised valves, with linear actuators and piston-cylinder mechanisms to control a soft colonoscope. The proposed design combines a precise control of the fluid pressure and volumes in each chamber.

1 Introduction

Colorectal cancer causes 1.9M new cases per year worldwide with almost 900K death [1]. Early detection is key, with a five year survival rate above 90% at stage one and below 10% at stage four [2]. There are several non-invasive screenings tests, however colonoscopy is the only procedure with dual capability to screen the colonic mucosa and to remove polyps [3]. The first screening of the entire colon and polypectomy by using an electrosurgical snare was performed in 1969 [4]. Since then, colonoscopy has been the gold standard for colorectal cancer [5], [6]. Due to limitations of the current procedure, such as the difficult learning process [7], discomfort for the patients, and in some cases, perforation of the colon [8], research institutes and industries are working on alternative, cost effective, and more efficient solutions. However, limited are the devices that have been granted CE mark or FDA approval. The designing of a medical device to screen the entire colon with on-board instrumentations has many challenges due to the slippery surface of the colonic mucosa and limited space inside the lumen [9]. Forces applied by the device for locomotion are essential to reduce pain and discomfort as well as to avoid any damage to the colonic mucosa. Soft robotics, in particular fluidic soft devices, can provide a valuable solution due to the mechanical properties that make a device intrinsically safe when interacting with human organs [10], [11],[12], [13], [14]. However, the elastic properties can cause instability issues, lack of precision in the control, and reduce the mechanical bandwidth. Instability can be related to the control strategy but also to the hardware that implements the control variable, such as pressure or volume of the fluid inside the device.

1.1 State of the art

The control of fluidic soft robots can have either on-board components or external components with tubes to inject the fluid in each chamber. The first robot with all the components on-board was presented by [15], with a chemical pressure generator for the activation of the pneumatic chambers. In a much bigger scale, a fully untethered quadruped robot with a length of 65cm and a weight of 5kg was designed with all the components on-board [16]. The air was generated by using an on-board electric pump and electric valves used to control the pressure inside each chamber. An autonomous soft fish with on-board control, valves, and a pressure regulator was designed to study biological fishes [17].

A small and compact wireless pneumatic hardware was designed to control chamber pressures in a pneumatic soft robot by using inlet and outlet valves, pressure sensors and a Bluetooth wireless communication [18], [19]. The control was implemented with a closed control loop at 1.5KHz.

The hardware proposed in this work has been designed to control a soft colonoscope that applies low pressure against the colonic wall, together with an effective locomotion solution experimentally validated in a plastic phantom, to inspect the large bowel [20].

1.2 Methods

Pressure sensors are often used to control fluidic soft robots due to, in some designs, a linear relation between pressure and displacement [20]. This requires a loop to be closed at a frequency above 1KHz to avoid instability. The use of valves reduces the overall volume of the hardware since one source of fluid can be used to control several chambers. The pressure in each chamber can be implemented by using an inlet and outlet valve. When the control variable is the volume, instead, a piston-cylinder can be used. The piston compresses the fluid according to its displacement and inner diameter (bore). However, this architecture will increase the overall size of the hardware compared to one that uses valves and an external fluid supplier.

The presented work describes a hardware that can be used to control a soft inchworm double balloon colonoscope by using a combination of piston-cylinder and valves. The hardware includes three linear actuators actuated by means of a piston-cylinder mechanism for each chamber, which uses a compact mechanical connection designed to reduce the overall space together with a low-cost stepper motor. By contrast, proportional valves are used to control the balloons. This hybrid solution has been proposed considering that the balloons must secure anchorage in different sections of the colon (which can reach a diameter close to 80 mm [21]), hence they require a large volume of air for their activation. This would require the use of a large piston-cylinder hardware, which would increase the overall size of the control unit. Two valves, one inlet (IV_i) and one outlet (OV_i), are used to control the diameter of each balloon and to secure anchorage while keeping the pressure against the colonic wall low in order to reduce pain and discomfort.

The hardware has been designed to control a soft inchworm colonoscope, which consists of two balloons connected by means of a three degrees of freedom (DOFs) soft pneumatic actuator (SPA) [20].

1.2.1 Control hardware

The control hardware consists of two units. One wired unit to control three piston-cylinders (UN_1), and the other one wireless to control the two balloons (UN_2). The control architecture is shown in Figure 1. UN_1 is dedicated to control the three DOFs SPA, while the UN_2 to control the two balloons, with two additional DOFs, for a total five DOFs. UN_2 design is reported in [18]

In UN_1, the piston-cylinder mechanism, PC_i, *i* (*i*=1,2,3), is controlled by using a stepper motor with the volume V_i related to the displacement of the piston. For simplicity this relationship is assumed to be directly proportional to the displacement d_{pi}, V_i=K d_{pi}. The mechanical design is shown in Figure 2. Each stepper motor is connected to a ball screw linear guide with a spool of 100mm. The actuator slide stoke guide is connected to a Festo pneumatic cylinder with a 25mm bore, and a 100mm stroke (DSNU-25-100-PPV-A), which is placed above the linear guide. The connection is made by using two rigid parts made from VeroClear (Tensile Strength 40 – 55 MPa (5,800 – 8,000 psi), Modulus of Elasticity 2,200 – 3,000 MPa (320,000 – 435,000 psi)) by using a 3D printed Stratasys Object30 Pro.

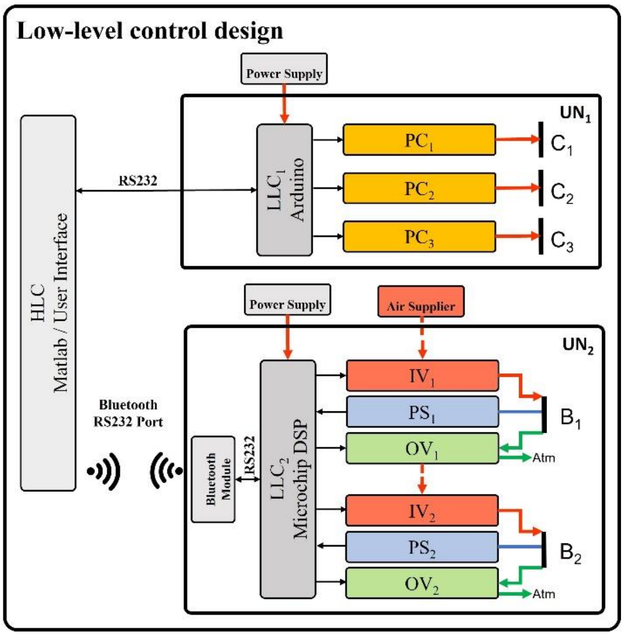

Figure 1 Architecture of the design implemented in the control units connected to the three piston-cylinder mechanisms to control the three chambers (C_1, C_2, C_3) and the two balloons (B_1, B_2).

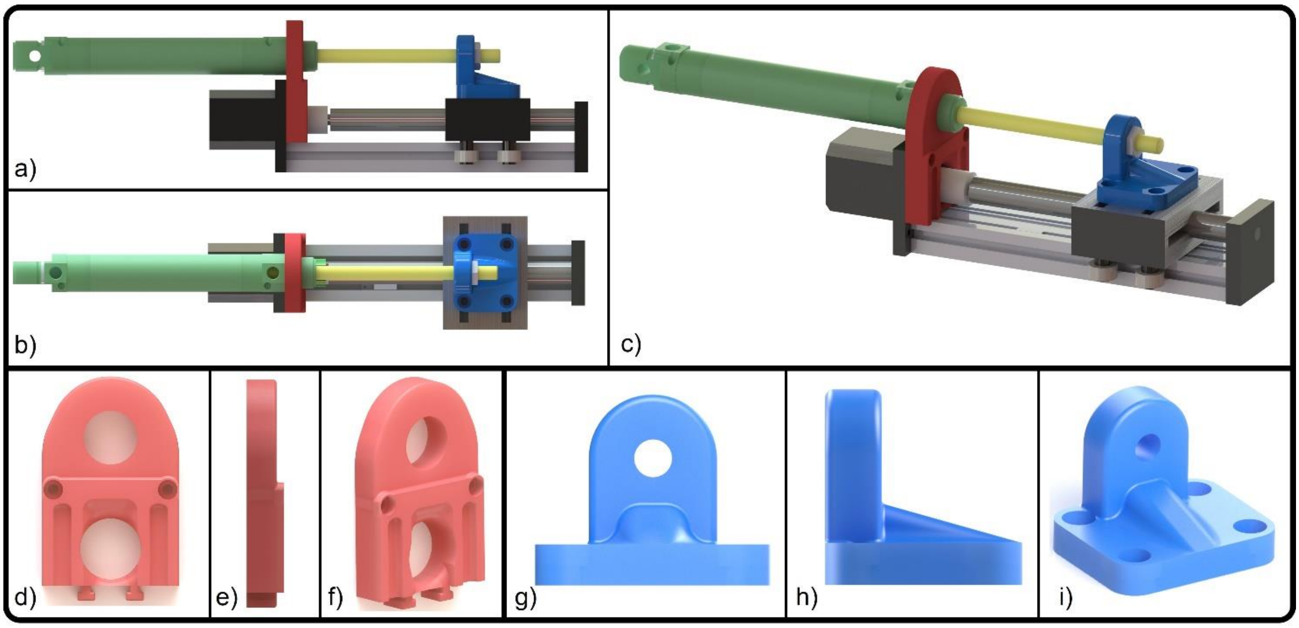

Figure 2: CAD renders of the mechanical components to control volume in one chamber. Piston-cylinder hardware is shown in subfigure a), b), c), where a) is the front-view, b) top-view, and c) a prospective view. Par_1 is shown in subfigures d), e), f), and Par_2 is shown in sub-figures g), h), i).

Figure 2 shows a CAD design of the part to control one chamber. This design reduces the overall length and weight of the hardware and makes it modular. One end of the cylinder is fixed to the slide stoke through Par_1, (Sub figure 2-d), e), f)) while the piston is fix to the frame of the guide through Par_2, (Sub figure 2-g), h), i)). A visual inspection of the mechanical connection does not show any deformation after an extensive use of the hardware. Each piston uses a 4mm push-fit connector to provide fluid to each chamber. A thread and a bolt in Par_2 fix the piston and are used to precisely adjust the displacement of the piston. The internal volume is controlled by using d_{pi} in the loop and a Proportional-Integrative (PI) controller. The use of stepper motors simplifies the implementation of the control of the position and speed of the piston, which is proportional to the input pulse frequency of the steps provided. The control of the stepper motors is implemented by using an Arduino Leonardo board together with low-cost stepper motor driver controllers (TB6600 4A 9-42V). The firmware is implemented in "C", runs two tasks, defined as a low-level control (LLC_1): $Task_1$, data communication with an external console; $Task_2$, implements three PI_i controllers for the speed of the three steppers motors. The firmware receives data from an external console where the high-level control (HLC) is implemented in MATLAB® Simulink. The HLC executes the speed for each actuator and receives back from the LLC_1 the position of each piston d_{pi}. The speed is controlled by using a Microsoft® Xbox controller.

UN_2 is dedicated to control the pressure inside the two balloons. The firmware is implemented in "C" code in a 16 bits Microchip DSP (digital signal processor), which runs three parallel tasks in the LLC_2: $Task_1$, is dedicated to the data communication with an external console; $Task_2$, implements the control of the pressure by using a PID_i and two proportional miniaturised valves, inlet and outlet. The HLC in the external console sends the pressure reference variable to be controlled inside each balloon.

The Microsoft® Xbox in the HLC facilitates the manoeuvrability of the soft colonoscope and the implementation of more advanced locomotion strategies.

The design of the UN_1 has a modular design which allows to include additional hardware, if this is required, increasing the number of chambers to control. This will be limited by the number of digital inputs available to the Arduino board. A higher number of modules will reduce the control loop sample time due to the increase of data sent through the serial communication.

2 Conclusions

A low-cost hybrid hardware to control a pneumatic soft device, specifically a five DOFs inchworm soft colonoscope, has been presented. This work can control pressure and volume of fluid inside each chamber independently. The combination of pneumatic linear actuators and proportional pneumatic valves allows the implementation of multiple control strategies. This can improve the precision and the implementation of different tasks, while reducing the stability problem related to the internal pressure as a single control variable. A HLC strategy can be implemented and validated. The components used for the development have been selected to be low-cost while having an effective control solution. The use of a Microsoft® Xbox controller facilitates the manoeuvrability of the device, and MATLAB® Simulink where the HLC is implemented, simplify the implementation and validation of different control strategies.

Additional work can be done to improve the proposed design. The use of stepper motors facilitates the LLC_1 and reduces costs. However, the lack of on-board position sensors reduces the speed of the movement. To avoid missing steps in the control, the top speed is limited. The power consumption is high even if the stepper-motors are holding a fixed position; this is due to the driver selected for the control. Brushless or brushed motors together with encoders can improve the performance, however, produce an increase in costs and complications in the implementation of the LLC_1. Pressure sensors can be used in the loop of the control of the volume of the fluid. This solution could be used to implement more advanced control strategies and to identify any issues in the controller like, for example, fluid leakage, or if an external force is applied.

This work focusses on the mechanical implementation and additional experiments are needed to identify the overall performance in terms of controllability and interaction with the external environment.

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