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An all soft, electro-pneumatic controller for soft robots

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Abstract—Despite an ever increasing variety of soft sensors and actuators, there are only a few entirely soft robots that integrate both modalities into an autonomous system. Often, a minimum set of rigid components such as microcontrollers, are embedded into soft systems, compromising their flexibility. This has led to growing interest in entirely compliant versions of controllers for soft robots. In this work, we present the first integration of two such soft control systems: the soft, bistable valve and the soft matter computer. By combining them we allow information to pass from the pneumatic to the electrical domain, enabling control of electric soft actuators with pneumatic control signals. Our work is an important step towards the development of fully compliant robots and machines.

I. INTRODUCTION

Despite recent advances in soft sensing [1], [2], [3] and actuation [4], [5], there are few examples of autonomous soft robots. One reason for this is the lack of soft material controllers, meaning the vast majority of soft robots are controlled by rigid electronic microcontrollers [6], [7], [8]. These rigid materials limit the flexibility of an otherwise soft system, and there is now growing interest in alternative soft material control approaches.

Existing controllers made from soft materials have largely relied on fluidic or microfluidic approaches. For example, Wehner et al. used a microfluidic circuit to control the arms of a soft octopus [9] and Mahon et al. developed a microfluidic hexapod walker [10]. However, microfluidic control schemes operate at low flow rates due to small channel sizes, meaning they are not well suited for generating the high pressures that are required for powering most pneumatic soft actuators (e.g., a typical fluidic elastomer actuator requires a pressure of 0.5 bar [11]). Rothemund et al. have shown how this limitation can be overcome by increasing the physical size of the fluidic channels [12], [13]. Their fluidic controllers are based on a soft, bistable valve [12] (see Figure 1), which uses the snap-through of a bistable

membrane to block or pass airflow. This valve has been used to implement soft versions of many fundamental electronic components, including a soft ring oscillator [14] and both volatile and non-volatile memory [13], [15].

This approach of pneumatically controlling soft robots using entirely soft logic gates replicates electronic digital control systems, providing a pathway towards increasingly capable soft controllers. However, soft pneumatic circuits are limited to controlling pneumatic actuators, preventing the use of the many soft actuators that are electrically or thermally controlled.

Recently, an electro-fluidic approach to the control of soft systems, known as the Soft Matter Computer (SMC) has been developed [16], [17] (see Figure 1). The SMC uses a pattern of alternating regions of conducting and insulated fluids to encode information. This information is then transduced by receptors embedded in a soft tube to generate an electronic control signal. However, the SMC currently requires a pump or other pressure source, to push the input through the tube. Existing soft robots that are controlled via an SMC have required the integration of a rigid peristaltic pump, introducing a rigid element into an otherwise soft robot.

In this work, we combine the soft, bistable valve with the SMC to develop an electro-pneumatic soft controller (EPC) that circumvents the limitations of each respective technology. Our approach allows digital pneumatic circuits to control electrically powered soft actuators such as shape memory alloys (SMAs) or ionic-polymer metal composites (IPMCs) via SMCs. We demonstrate the EPC by cyclically controlling an SMA-driven soft finger without the use of a rigid pump. The integration of two complementary control frameworks presents a necessary step towards autonomous and untethered soft robots.

II. PRINCIPLE OF OPERATION

The soft valve uses the bistability of a soft membrane to switch airflow (analogous to CMOS technology) [13]. The valve consists of two chambers that are separated by a bistable membrane, with soft tubing leading through each chamber. When the membrane is in the bottom position, the tubing in the bottom chamber is kinked, blocking airflow, while allowing air passage through the top tubing. The membrane can be flipped from the bottom to the top position by applying a pressure to the bottom chamber such that the pressure difference between the top chamber ($P+$) and the bottom chamber ($P-$) is greater than the critical switching pressure of the membrane. When the membrane flips to the

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Fig. 1. **Integration of the soft, bistable valve with the soft matter computer (SMC).** (A) Image of the soft, bistable valve controlling an SMA driven soft finger via an SMC and coupling element. (B, C) Working principle of the electro-pneumatic controller. The soft valve consists of two chambers separated by a bistable membrane. When the membrane is in the bottom position (B), the tube connecting P_{sup} to the output is kinked, and P_{atm} is connected to the output. Applying pressure to the control input P_- (C) causes the membrane to flip, kinking the tube connecting P_{atm} to the output, and connecting P_{sup} to the output. This causes the coupling element membrane to deform, advancing the SMC input. When the conductive fluid enters the electrode region, the electric circuit is closed, powering any electrical load in series with the SMC electrodes

top position, the tubing in the top chamber is kinked, allowing airflow only through the bottom tubing. This mechanism allows the switching of high pressures, using comparatively smaller control pressures.

An SMC consists of one or more conductive fluid receptors (CFRs) and a fluidic input [17][16]. The fluidic input consists of alternating regions of conductive and insulating fluids, where the length of each region encodes information. A CFR consists of pairs of electrodes embedded into a flexible tube. When the conducting fluid enters the receptor region, the electrical circuit is closed, transducing the fluidic signal into an electronic signal that can control any electrically-driven soft actuator connected in series with the CFR electrodes.

Soft matter computers operate in either digital or analogue mode. In this paper, we use only digital mode SMCs, in which an SMC outputs binary *zero* (infinite resistance) when the insulating fluid is within the receptor region and binary *one* (10 Ω resistance typically) when the conducting fluid is within the receptor region.

To connect a soft bistable valve to the SMC, we developed a simple coupling element to transduce the pressure output

Fig. 2. **Switching of the electric output of the SMC using a pneumatically-driven soft, bistable valve.** The first plot shows the current (blue line) and activation (red line) of a shape-memory-alloy soft actuator. The bottom plot shows the pressure input P_+ of the bistable valve (varied manually). As the conductive fluid of the SMC input is initially in-line with the CFR electrodes, the SMC output is switched off when the valve pressure is high.

of the soft valve into a flow input for the SMC. The coupling element (Figure 1) consists of two chambers separated by a thin membrane. When pressure is applied to one chamber, the membrane deforms until the restoring force due to the membrane deformation is equal to the force applied by the pressure difference (Figure 1C). The deformation of the membrane also increases the pressure inside the second chamber. The increase in pressure advances the input of the SMC; conductive fluid is pushed towards the CFR electrodes, completing the electrical circuit. When the soft valve is switched off, the coupling membrane returns to its resting position. This reduces the pressure in the second chamber, withdrawing the input to the SMC and switching it off.

The deflection of the coupling element membrane due to the applied pressure is proportional to the area of the membrane, A , and inversely proportional to the cube of the membrane thickness, t . This allows control of the distance the conductive fluid (input of the SMC) is moved by a particular supply pressure, P_{sup} . The input of the SMC may be initially positioned before or in-line with the CFR electrodes, corresponding to a normally open, or normally closed circuit, respectively.

To fabricate the coupling element, we 3D printed molds for the element body and the two end-caps, using a Stratasys Connex printer and Verowhite resin. We used Eco-flex 00-30 to cast the three components, which we subsequently sealed with Sil-poxy silicone glue. We cut holes into each end-cap and inserted and glued silicone tubing (3mm inner diameter) in place using Sil-poxy.

III. RESULTS

We use the coupling element to enable a soft, bistable valve to control an SMA driven soft finger (Figure 2). The SMC was pre-loaded with a 30 mm long slug of saturated salt water positioned in-line with the CFR electrodes (i.e. a normally closed configuration). The pressure in the top

Fig. 3. **Actuation of a soft actuator, using a SMC that is controlled by a soft ring oscillator.** (A) Image of the electro-pneumatic controller consisting of the soft ring oscillator, a soft bistable valve, a coupling element, and the SMC. (B) A diagram of the controller. (C) A plot of the current through the SMC. (D) A plot of the varying pressure that is output by the soft ring oscillator. The soft ring oscillator creates an oscillating pressure output from a constant input pressure.

chamber of the bistable valve was unconnected (i.e. $P_- = P_{atm}$), the pressure in the bottom chamber of the bistable valve (P_+) was measured with a pressure sensor (Honeywell HSCDNB100MDAA5, Digikey). The state of the SMC was determined by measuring the voltage drop across a 0.1Ω resistor placed in series with the CFR electrodes.

When we manually varied the control pressure (P_+) of the bistable valve, the input of the SMC advanced, breaking the electrical circuit and switching the SMA off. Figure 2 shows the electric current flow through the SMC electrodes (top) and control pressure applied to the bistable valve (bottom). The soft valve is able to repeatedly control the output of the SMC, with an average latency of 0.1 seconds.

To further demonstrate the potential of the integration of the soft, bistable valve with the soft matter computer, we configured three soft valves into a ring oscillator [14], and actuated the SMC with a soft valve and coupling element that was connected in series with the oscillating output of the ring oscillator (Figure 3). The output of the SMC was connected to a shape-memory-alloy based electric soft actuator. The soft ring oscillator is able to control the SMC, with the SMC signal closely following the ring oscillator output.

IV. DISCUSSION & CONCLUSIONS

In this work, we introduce an electro-pneumatic controller capable of transducing information from the pneumatic to

electrical domain. By replacing the rigid peristaltic pump from our previous work [16] with soft material valves and a coupling element, we have taken an important step towards the development of entirely soft robots. Furthermore, by enabling digital pneumatic control systems to interface with electronic actuators, we increase the options for designing all soft, autonomous robots, including using electrical or thermal actuators that are capable of undergoing large strains [18] or generating high specific stresses [19].

This increase in actuator choice comes at the cost of an increase in the complexity of the power system, as the EPC requires both pneumatic and electrical power sources. Compared to digital pneumatic circuits, the EPC reduces the demand placed on the pneumatic power source, with only pressures sufficient to switch the bistable membrane required, potentially enabling the use of on-board pressure generation systems [20], while also allowing the use of high energy density lithium polymer batteries. The SMC also requires electronics to generate an AC voltage source, however, we are currently investigating alternative conductive fluids to overcome this limitation.

Joining the soft valve and SMC through a connecting element also introduces an average latency of 0.1 seconds between the bistable valve switching and the activation of the SMC. This latency is largely due to the time required for stretching the coupling element membrane and for the SMC input to move through the tube. By reducing the initial separation between the fluidic input and the CFR electrodes, this latency can be reduced.

Previous SMC-powered soft robots have used a rigid peristaltic pump to drive the input signal around a circular tube. This corresponds to an input which repeats with a period given by the flow rate of the SMC and the length of the tube. The soft ring oscillator drives the SMC input forward and back. When the SMC input is driven in reverse, this corresponds to a reversal of the information encoded in the input. This limits the soft ring oscillator-driven SMC to generating signals which are symmetric.

Although we have demonstrated integration of the soft valve and SMC, this integration is only possible in one direction. An SMC cannot currently control a soft valve, and we are working on a mechanism to enable information to travel in both directions.

Our vision for the future of soft robotics is the development of untethered, autonomous, entirely soft robots. For this to be achieved, it is necessary to increase the complexity of the signals that can be generated by soft matter controllers. More complex control signals could be generated by leveraging the analogue mode of SMCs, by making use of soft equivalents of digital logic components, or by allowing the SMC input program to be modified during operation.

This work introduced an easily fabricated coupling mechanism that can be used to integrate the soft, bistable valve with the soft matter computer to create an electro-pneumatic controller. By enabling digital pneumatic circuits to control electrically powered soft actuators, this work represents a step towards untethered and autonomous soft machines.

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