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Soft Non-Volatile Memory for Non-Electronic Information Storage in Soft Robots

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***Abstract*—Pneumatically operated soft robots require complex infrastructure for their operation: microcontrollers must control hard pneumatic valves via power electronics. Although soft digital logic gates based on soft valves have been demonstrated as a replacement for electronic control, the development of memory from logic gates is cumbersome (three logic gates with mono-stable membranes for the development of a single S-R latch), and such memory is only capable of holding, but not storing, information; after a power reset, the membranes relax to their idle states, and the information is lost. In this work, we introduce a soft memory device with a bistable membrane that allows the permanent storage of binary information in soft materials, and we demonstrate its writing and erasing operations. We also introduce a new type of pneumatically-driven soft display, the soft bubble display. We connect the display to our soft memory device to visualize the information that is held in the memory. Our work highlights the importance of material-based memory and its future use for programming soft robots.**

Keywords—Soft computation, sequential logic, soft bubble display

I. INTRODUCTION

Pneumatically-operated soft robots allow for safe interaction with humans, and they enable handling of delicate objects including living organisms (eggs, mice, etc.); they therefore present a new opportunity to directly incorporate artificial intelligence schemes for truly collaborative use [1]–[3]. These robots are typically interfaced with microcontrollers, power electronics, valves, and pumps to control the on-off switching of airflows [3]–[5]. This infrastructure is usually located externally to the robot to avoid jeopardizing the safety and compatibility with humans and animals, and is connected to the robot via a tether [3], [6]. Conversely, integrated versions of soft robots, in which all electric and electronic components are embodied, reduce their original advantages such as low weight, resistance to impact [1], [7], [8], and resistance to corrosive chemicals and harsh environments [9], among others.

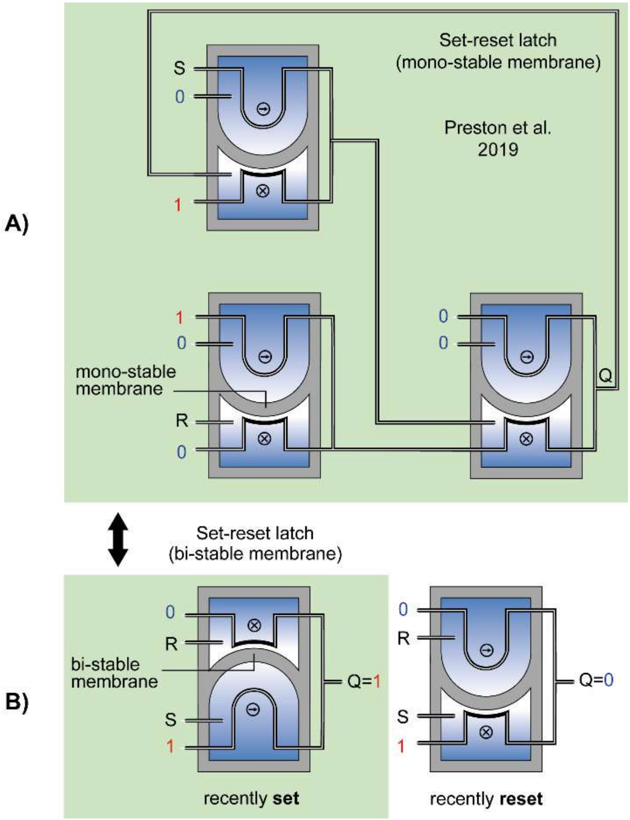

Fig. 1. (A) Previously, three soft valves with mono-stable (under atmospheric pressure) internal membranes were used for the design of a set-reset (S-R) latch [15]. This S-R latch allowed the temporary storage of information; once the supply pressure was cut off, however, the membranes flipped back to their idle states and any stored information was permanently lost. (B) Here, we propose a new memory device that only requires one instead of three soft valves; the new device possesses a bistable membrane instead of a mono-stable membrane, allowing the permanent storage of information, hence referred to as non-volatile memory. Once the membrane has flipped, it remains in its position until pressurized from the opposite side.

Wormbot is a classic example of a soft robot that embodies electronics for control purposes at the cost of reduced material compliance; circuit boards were used for the control of electromagnetic actuators and incorporated into the body segments of the worm [10]. Soft *electronic* strategies for the control of soft robots include the use of conductive fluids in microfluidic circuits to interface the fluidic with the electric domains, proposing a substitute for electric “hard” wires [11]. Based on that idea, Garrad et al. developed a conductive fluid receptor, a transducer that converts fluidic signals into electric signals [12]. While the electric output of their transducer cannot be the fluidic input of a concurrent transducer, their elements show promise for the development of electric

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interfaces between fluidic control circuits and nonfluidic (electric) soft actuators. Wang et al. developed a highly conductive polymer using additive-assisted enhancers that resulted in a morphology that is beneficial for both high stretchability and conductivity [13]. Teng et al. demonstrated the integration of soft sensor systems based on EGaIn with conductive thread establishing an interface between soft and hard conductors in soft materials [14].

Recent work on soft controllers has created a new pathway towards the *non-electronic*, integrated control of soft robots using solely compliant materials. A soft valve can be used as a transducer that interfaces microfluidic circuits with pneumatic actuators switching a signal of high pressure with a signal of low pressure (cf. electric relays) [7]. The same valves can be configured as logic gates (NOT, AND, and OR gates) that allow for the integration of combinational logic including set-reset latches, two-bit shift registers, leading edge-detectors, digital-to-analog converters, and toggle switches [15]. If three NOT gates are connected in series and the output of the final gate is connected to the input of the first gate, a ring oscillator (cf. computer clock) transduces a signal of constant pressure into signals of temporarily varying pressures [16].

Microfluidics is yet another technology that can be used for the *non-electronic* control of soft robots. Wehner et al. demonstrated a microfluidic circuit for the control of a small soft robot that operated at low rates of airflow [17]. The robot autonomously regulated the catalytic decomposition of an on-board monopropellant fuel supply. The gas generated from the fuel decomposition pneumatically powered a fluidic network that resulted in actuation. The use of microfluidic circuits for the control of soft robots was taken one step further by Mahon et al. who developed a "macrofluidic" circuit, scaling up a microfluidic circuit to the macroscale, to power a series of vacuum driven actuators, integrating a simple state machine [18]. Although their circuit was a hybrid of soft and hard materials (PDMS sandwiched between two acrylic sheets), the implementation of completely soft macrofluidic circuits could be a feasible next step.

While early steps have shown great promise, developing non-electronic control for soft devices in general is challenging. Besides the difficulty of developing control that can be easily built and used by others, determination of which low-level functionality a robot requires to perform a specific task presents additional design considerations.

Electronic components such as microcontrollers are highly sophisticated devices that are packed with immense functionality ranging from analog-to-digital converters to specialized communication buses (e.g. I2C or SPI). When it comes to replacing electronic functionality with non-electronic soft devices, soft computation has not reached the maturity to be able to implement entire microcontroller-like devices. As intermediate goals, we need to identify specific functionalities of microcontrollers that will help future soft robots in solving increasingly complex tasks. We envision that the emerging field of soft computation in soft robotics will ultimately generate completely soft, general-purpose controllers for soft robots that allow for various input and output functionalities, the capability to compute and store data, and programmability.

In this article, we focus on the development of soft memory (Figure 1). There are two main types of memory, volatile and non-volatile memory. Non-volatile memory retains its data when switched off, while volatile memory loses its data. Both types of memory are used for the storage of data; ROM (Read Only Memory) is typically non-volatile memory and can contain crucial programs that are essential for the operation of a system such as the BIOS (Basic Input Output System) of a PC; RAM (Random Access Memory) is volatile memory and is used, for example, by standard software applications such as word processors to store temporary data. RAM is usually faster, less expensive, and more compact than ROM. The *ideal* memory, however, is: (i) non-volatile, (ii) fast, (iii) large in capacity, (iv) low in cost, and (v) allows for writing and erasing of information [19].

In this paper we introduce a non-electronic, non-volatile memory for soft robots. The main contributions of our work include:

1. A non-volatile memory device that stores binary information, and "remembers" its state even after a disruption of system supply pressure.
2. A pneumatic soft display (referred to as "soft bubble display") with a single input that indicates binary "1" and binary "0" through black and white membranes.
3. Demonstration of the writing and erasing of information in our memory, integrating the memory device with the soft display, and a discussion on why memory is becoming an important research direction within soft computation.

II. DESIGN

A. *Non-Volatile Memory Using a Bistable Membrane*

Our non-volatile memory, with the function of an S-R latch with permanent storage capability, consists of an elastomeric cylinder that houses a bistable membrane and two tubes (Figure 2A). The membrane can occupy one of two states, i.e. the top or bottom positions. In the top position, the membrane kinks the top tubing and allows air passage through the bottom tubing; conversely, in the bottom position, the membrane kinks the bottom tubing and allows air passage through the top tubing (Figure 2B). The membrane itself can be flipped by applying pressure to the corresponding pressure chambers.

The memory device is based on our previous work on soft valves using membranes which were mono-stable under atmospheric pressure [7]. Our memory device is a derivative of the soft valve; we altered its design to fabricate a device with a truly bistable membrane. The membrane thickness changed from 3 mm to 2 mm compared to our prior work [7]. Our memory device is configured here as an S-R latch, a device with two stable states that can be used to store information. Previously, we built an S-R latch from *three* soft valves with mono-stable membranes [15]. This version was cumbersome to build and only allowed the temporary storage of data (volatile memory). Once the supply pressure was disconnected from the latch, the membranes flipped back to their idle states. Here we substitute the previous design of the S-R latch, consisting of three soft valves with mono-stable membranes, with a single soft valve with a bistable membrane (Figure 1). This new S-R latch not only consists of fewer devices (one instead of three), but also allows the permanent storage of information due its bistable membrane; a bistable membrane remains in the position it was set even after a discontinuation of the supply pressure.

Figure 2A shows a picture of the actual memory device. Figure 2B illustrates its principle of operation. Our non-volatile memory device has four inputs and two outputs; the two outputs are routed together to form a single output "**Q**". The output allows the reading of the memory; any pneumatic load can be attached to the output of the memory. The control signals "**S**" and "**R**" refer to **"SET"** and **"RESET"** and allow the writing and deleting of information inside the memory device. The control signals are directly connected to the membrane chambers inside the device and are responsible for the flipping of the membrane in either direction.

In Figure 2C, we characterize our memory device. The snap-through pressure—the pressure that is required to move the membrane from the bottom to the top position—is 8 kPa; the snap-back pressure—the pressure that is required to move the membrane from the top to the bottom position—is 1 kPa. The difference in snap-through and snap-back pressures can be explained by the membrane design and material characteristics [7]. When the membrane flips (to either side), a temporary pressure reduction occurs due to a volume displacement of air as the membrane moves.

The measurements in Figure 2D detail the operation of our memory device. Binary "**0**" relates to atmospheric pressure (0 kPa relative pressure), and binary "**1**" relates to supply and control pressures of 45 kPa. The supply pressure is the pressure that the memory device outputs if it is set ($\mathbf{Q = P_{supply}}$), atmospheric pressure is the pressure that the memory outputs if it is reset ($\mathbf{Q = P_{atm}}$). Here, we chose 45 kPa because it is the actuation pressure of our soft display (Figure 3). We use the soft display to visualize the information that is held in our memory devices. Although it only requires 8 kPa to write (and 1 kPa to erase) information from the memory (Figure 2C), the memory device can be operated at pressures of up to 45 kPa. In general, the supply pressure is independent of the control pressure and can be changed based on the pneumatic load that is attached to the memory.

We used DragonSkin 10NV and Smooth-Sil 950 for the fabrication of our memory devices (Smooth-On Inc.). We prepared their prepolymer mixtures in three steps: (i) adding both components, (ii) stirring the mixture manually for two minutes, and (iii) degassing the mixture under vacuum for 10 minutes. The degassed prepolymer elastomers were filled into 3D-printed molds and cured to create the valve

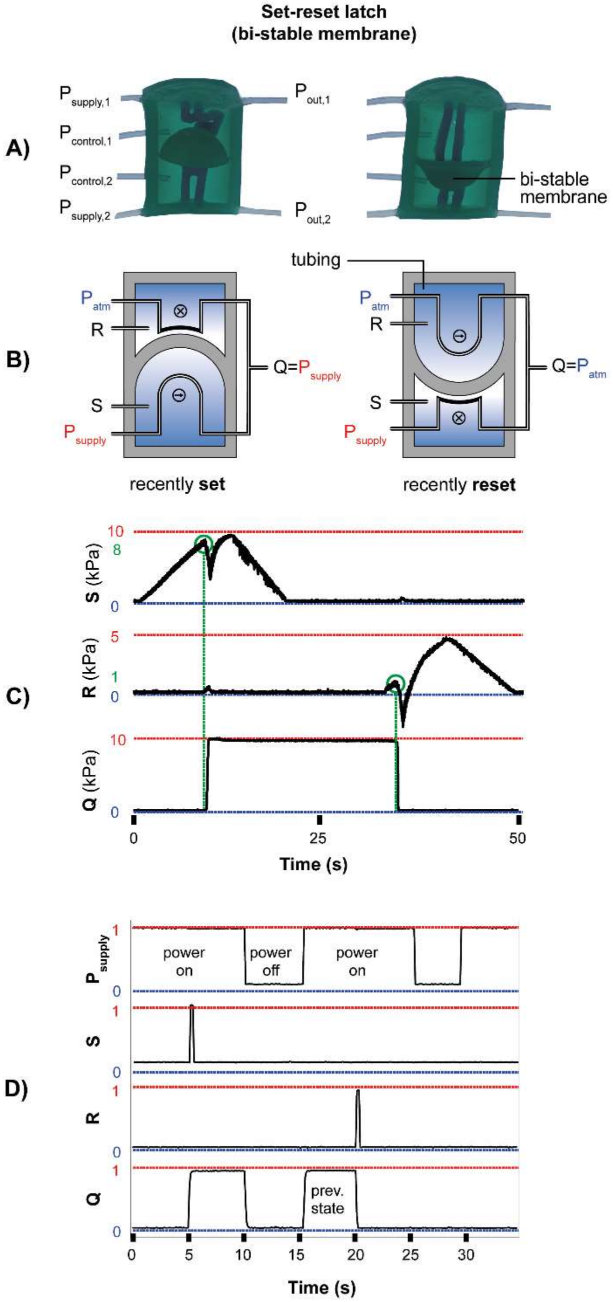

Fig. 2. (A) Crossection of a soft valve with a bistable membrane (membrane thickness of 2 mm and an opening angle of 90º) [7]; the membrane remains in its position unless flipped via external pneumatic actuation. (B) The device is configured as a set-reset latch for the storage of information. The S and R lines set and reset the latch; if the latch is set, it outputs supply pressure, and if it is reset, it supplies atmospheric pressure. (C) Characterization: it requires a higher pressure to flip the membrane to the top side (S = 8 kPa) than to the bottom side (R = 1 kPa), which can be explained by the membrane design and material characteristics [7]. (D) A power outage does not affect the storage of information, and hence the soft valve with a bistable membrane configured as an S-R latch acts as a non-volatile memory device. In this example, our supply and control pressures match the actuation pressure of our soft display (45 kPa).

components. We used Silc Pig (Smooth-On Inc.) to change the color of the soft valve to green. To fabricate the tubing inside the valve, we filled a syringe with the prepolymer mixture of Smooth-Sil 950 and degassed it in the syringe for another ten minutes before injecting its content into the assembled mold. Mold CAD files are available upon request. For additional information on the fabrication process, we refer to our previous publication on soft valves [7].

B. *Soft Bubble Display*

Our soft bubble display consists of an array of pixels (here two rows and one column). The display can be extended to an arbitrary number of pixels (the mold is easily extendable). A soft pixel consists of four layers (Figure 3): (i) pressure chamber, (ii) membrane layer, (iii) slit layer, and (iv) display chamber. The pressure chamber contains the inlet for pressurized gas and forms the bottom layer of the pixel; a thin black membrane layer (0.5 mm) seals the pressure chamber, and the membrane expands if the pressure chamber is pressurized. The thin white slit layer (0.5mm) covers the black membrane layer; it has a cross-shaped slit that allows the membrane layer to bypass if actuated. If the pressure chamber is pressurized, the black membrane expands and pushes through the slit layer into the display chamber. A soft pixel requires an actuation pressure of 45 kPa to fully deflect into the display chamber (Figure 3). Once the display pixel is unpressurized, the membrane pulls back and the white slit layer covers the black membrane layer.

Our pneumatically actuated soft bubble display can be used for the visualization of pressure "states", such as from memory or other pneumatic loads including grippers. Each soft pixel can be pressurized individually (i.e., there is a 1-to-1 mapping of pixel input and pneumatic load). The display is robust to failure; we tested it for more than 15,000 actuation cycles. Our design has the advantage of displaying information without the use of liquids; liquids can diffuse through elastomers or evaporate, which limits their use to finite times (on the order of days) at or near room temperature [20]. In addition, pressurized air is readily available, whereas liquids in closed hydraulic systems are cumbersome to sustain.

We used DragonSkin 00-30 for the fabrication of the pressure and display chambers and DragonSkin 10NV for the fabrication of the membrane and slit layers (Smooth-On Inc). We filled the prepolymer elastomers into the 3D-printed molds and let them cure to create the pressure and display chambers. The membrane and slit layers were cast on a glass surface. We used a 3D-printed mask that helped guide our scalpels when cutting the cross into the slit layers. We used Silc Pig (Smooth-On Inc.) to make color changes to the elastomers. We used black pigments for the membrane layer and pressure chamber, and white pigments for the slit layer and display chamber. We punched a hole into the pressure chamber of a soft pixel by using hole punch pliers. The hole accommodated soft PVC tubing. We glued the layers and the tubing (after insertion) with Dowsil RTV Sealant 734 (Amazon.com). Mold CAD files are available upon request.

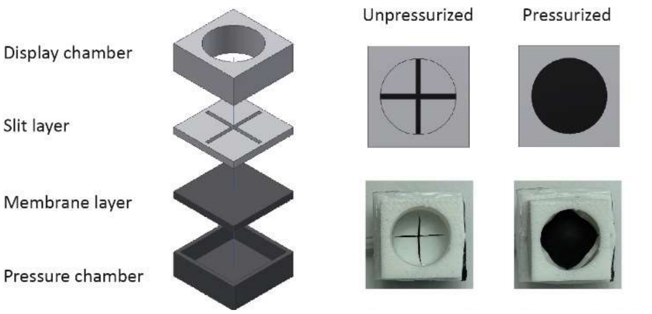

Fig. 3. A pneumatically actuated pixel from our soft bubble display. The entire device consists of soft materials. Four layers form the soft pixel (from the bottom to the top): pressure chamber, membrane layer, slit layer, and display chamber. The pixel has a single input and requires a pressure of 45 kPa to actuate fully. If connected to atmospheric pressure, the black membrane layer retracts and only the white slit layer becomes visible.

III. EXPERIMENTAL VERIFICATION

Figure 4 shows our experimental setup. It consists of a pressure manifold with four individual switches that output control pressure when actuated and output atmospheric pressure when not actuated. The four switches are connected to the control lines (**S1**, **S2**, **R1**, **R2**) of two memory devices (**M1**, **M2**). The outputs of the memory devices are connected to two pixels of the soft bubble display (**D1**, **D2**). The soft bubble display "reads" the memory and visualizes its "states". The control lines enable the writing (set and reset) of information into the memory.

If **S1=1**, **M1** outputs $\mathbf{Q=P_{supply}}$ to **D1**. $\mathbf{P_{supply}}$ refers to the supply pressure of 45 kPa. If **R1=1**, **M1** outputs $\mathbf{Q=P_{atm}}$ to **D1**. $\mathbf{P_{atm}}$ refers to atmospheric pressure. The same holds true for **M2** and **D2**. If the supply and control pressures are cut off ($\mathbf{P_{supply}=P_{control}}$=0 kPa), the bistable membranes of **M1** and **M2** remain in their positions storing the most recent states of information. If the supply pressure is reestablished, **M1** and **M2** output their memory states to the soft pixels **D1** and **D2**. The memory can be manipulated again if the control pressure is reestablished too.

We refer to our supplemental video for the full experiment that demonstrates non-volatile memory storage using soft materials. In our video, we demonstrate all combinations of information storage for two memory devices. Two memory devices allow for the storage of two bits. Two bits allow for the storage of $N=2^2$ states. In addition, we use a side cutter to physically cut off the supply and control pressure lines. We demonstrate that the memory safely stores its most recent information after a pressure outage.

IV. DISCUSSION

In this paper, we introduce a non-volatile memory device that is easier to make than its volatile counterpart. We replace a volatile memory that consists of three soft valves with a non-volatile memory that consists of a single soft valve. This work complements our previous efforts on soft valves and their use as digital logic gates and oscillators, and adds the capability of *non-volatile* memory. This paper also draws attention to soft-material-based, non-volatile storage of information without the use of electronics.

A. Importance of Memory in Soft Robots

Memory plays a paramount role in computer architecture; we could have not drafted this manuscript without memory (in our computers). Memory allows the storage of information. In the context of soft robotics, our memory devices can be easily used in future designs of soft robots. They can be used to encode entire programs into soft robots without necessitating electronics. Memory can also be used to change the program of a soft robot expanding its versatility and usefulness in applications. In general, the availability of memory determines whether a robot can execute reactive behaviors using combinational logic or increasingly sophisticated behaviors using sequential logic.

B. Combinational Logic

Combinational logic, also called time-independent logic, is memory-less. Such logic circuits only depend on the current values of inputs. For example, a reactive robot behavior would be: "if the pressure sensor detects an obstacle," then "move right". A logic gate is another example of a combinational circuit. An AND logic gate only outputs binary "1" if all of its inputs are binary "1"—the inputs do not have to be activated in specific sequence, only at the same time. Modern robotics would be unthinkable without memory. In fact, the requirements for computation and memory in conventional robots are continuously growing to accommodate increasingly complex algorithms (e.g. for machine vision—the ability of a computer to "see"). It is, however, possible to assemble memory from combinational logic; a *volatile* S-R latch can be built from a total of three logic gates (NOT, OR and AND gates) [15].

C. Sequential Logic

Sequential logic, also called time-dependent logic, necessitates memory. Sequential logic depends on both the current and previous values of inputs; previous values of inputs require memory for their storage. For example, a sequential robot behavior would be: "if the pressure sensor has gone off three times," then "move right," and then "move straight". In this case, we need memory to keep track of the number of times the robot has collided with its environment (determined by the sensor), and which actions have already been executed. Finite state machines (FSMs) are implementations of sequential logic; an FSM has a finite number of inputs, outputs, and states. States are kept track of during operation and therefore require memory. An FSM transitions from one state to another (e.g. from "moving forward" to the "moving left" state) based on stimuli from inputs (e.g. a pressure sensor that goes off because the soft robot collided with a wall).

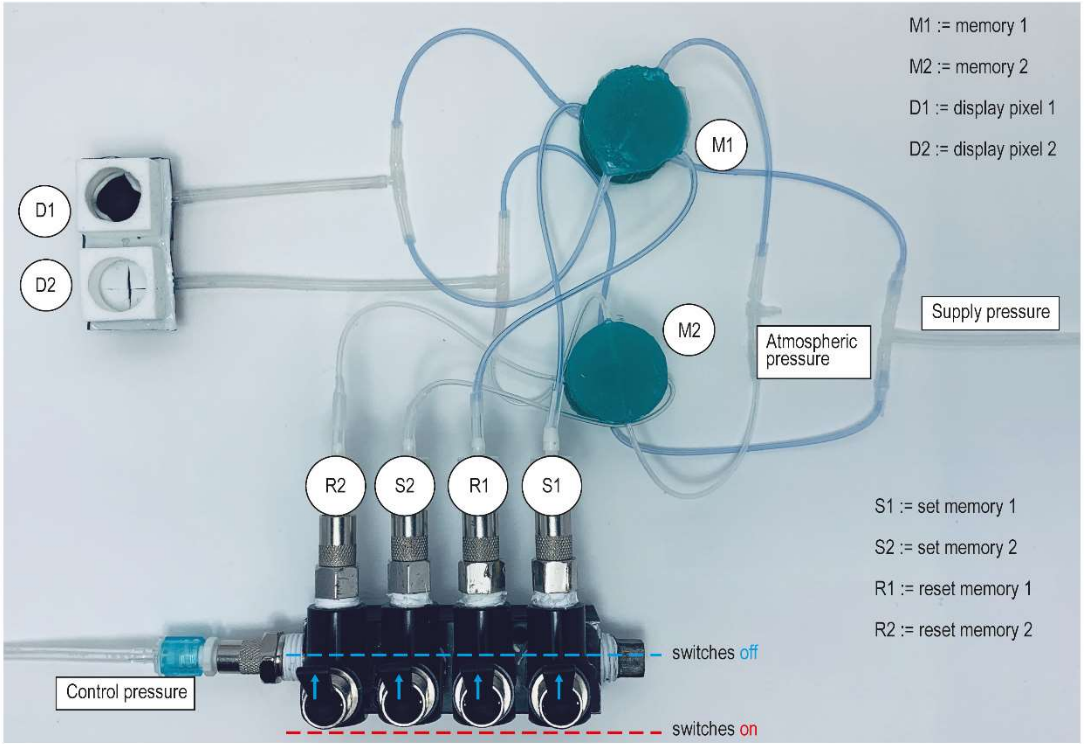

Fig. 4. Experimental setup demonstrating the non-volatile storage of information in soft matter. We connected the four outputs of our pressure manifold to two non-volatile memory devices. The S lines are used to store information in, and the R lines are used to reset (delete) information from, the memories. The control pressure is solely used for the S and R lines (for the flipping of the bistable membranes inside our memory devices). The supply pressure depicts the signal that is being exerted by the memory device if it was recently set by the S line. The soft display depicts a pneumatic load that in this case indicates the state of the memory device. Here, memory device **M1** was recently set, hence display pixel **D1** is actuated. Note that the control signals are all in the off-state, however, the memory exerts a pressure signal because it was recently set.

D. Pulldown Resistors

In microfluidic logic, pulldown resistors are typically used for the deflation of previously actuated pathways evoking a constant airflow at the on-state of pneumatic loads. In our case this cost is eliminated by having derived our design from the soft valve architecture. At any given time either supply or atmospheric pressure is connected to the output of the memory; pulldown resistors are not required to ground previously actuated pathways. This behavior can be compared to CMOS technology, where, in a transistor pair, one transistor is always switched on while the other transistor is switched off, reducing static power consumption [21].

E. Size and Scaling of Memory Devices

The bistable membrane of our non-volatile memory can be cast from a single mold; our membrane itself is therefore easily scalable. We also started experimenting with the size of our membrane. Membranes that are smaller in size change their properties, such as switching pressures [7]. Membranes that are fabricated from materials with a higher Young's modulus will require higher pressures to be flipped.

The internal tubing and interconnections to the "lids" of each chamber make the fabrication process of our memory device more challenging, mostly due to the multi-step casting process and the interconnecting of components, and currently prevents us from scaling them in large numbers. For practical reasons, to scale our memory device in size (e.g. smaller) and to large numbers, the internal tubing has to be reengineered. The tubing and connections could, for example, be made from a single mold, thereby reducing the total number of required fabrication steps.

Creating memory arrays from elastomeric (and even biodegradable) polymers utilizing material instabilities is a task worth pursuing, since such memory arrays will change the landscape of truly soft robotic systems in their capability to execute critical (and sophisticated) tasks in situations that cannot afford electronics either due to the potential risk of polluting the environment, or vulnerability to corrosive, magnetic, or radioactive environments, among others.

V. CONCLUSION

The membrane of a soft valve can be designed for bistability depending on its membrane thickness and opening angle. A soft valve with a bistable membrane can be configured as a non-volatile memory device that can be used for the storage of information, such as the information generated by sensors or internal computation. The information remains stored in the memory even after a discontinuation of pressure. Memory complements current efforts in soft computation and encourages the development of sequential logic, i.e., the design of soft circuits that take both current *and* previous inputs into consideration. Robots that use any type of memory will exceed purely reactive robot behaviors and will start executing more complex tasks (e.g. entering a building and leaving it by reversing the sequence of steps the robot has taken), with the opportunity to store and dynamically alter entire programs of software in soft matter.

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