A Modular Approach to Design Multi-channel Bistable Valves for Integrated Pneumatically-driven Soft Robots via 3D-printing

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***Abstract*— A pneumatic system that transmits power via the force of compressed air is an essential component of an air-driven soft robot. Pneumatic valves are one of the key parts of this system. However, the development of soft or electronics-free valves for soft robotic applications is in its infancy, with only a few 2/2 way valves developed. Previous research has shown demands for a complex pneumatic system that can regulate the airflow in multiple channels or switching the pressure within a chamber between multiple states. Hardware redundancy is found in such complex pneumatic circuits if only 2/2 way valves are available for the system design. To increase the design freedom, this paper presents a modular approach that integrates multi-channel modular valve units and bi-stable structures for the conversion of pneumatic signals. By utilising soft-material 3D printing, the 3/2-way valve, 4/2-way valve and 5/2-way valve design are proposed in this paper to control multiple air channels simultaneously. The modular design of these 3D printed multi-port valves allows quick design and fabrication solutions of a complex electronics-free pneumatic system by reassembling different modular units of the valve. Experiment characterization of the multi-channel valves shows maximum allowable pressure at 187.2 kPa and a flow rate of 7.42 L/min under 50 kPa pressure loss. A demonstration of controlling four states of a dual-chamber soft robotic arm with only two modular multi-chamber valves was included, showing reduced valve units and overall weight compared to conventional electronics-free 2/2 way valves.**

I. INTRODUCTION

Pneumatic soft robots make use of the interaction between compressed air and soft elastomeric materials to achieve high adaptability and compliance. This mechanism has drawn attention from many researchers due to various advantages, including low cost, flexible manufacture choices, safe human-robot interaction and adaptability to environments or objects with unknown kinematics or dynamics [1]. These valuable characteristics lead to the development of various pneumatic actuators with different structures, motion, pressure ranges, and fabrication methods [2], [3]. However, the control of these actuators requires complex pneumatic systems which consist of rigid solenoid valves, electric pumps, and conventional electronic controllers [4], [5], [6]. The existence of these tethered external rigid pressure systems significantly limits these robots' mobility and application fields, especially for those soft robots designed for extreme environment operations (e.g., nuclear plant exploration with high-radiation, tissue interaction during metal-free scenarios in

*This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) Grant EP/V000748/1; S. Wang was supported by the CSC-PAG Oxford Scholarship for his DPhil study.

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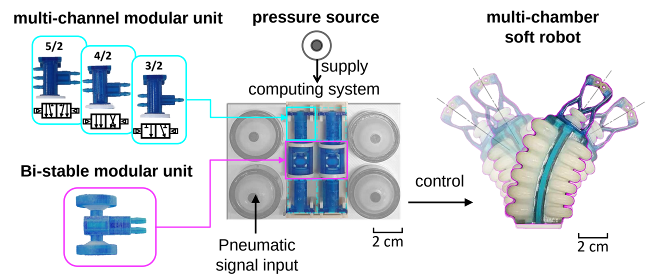

Fig. 1. The modular design of the 3D-printed multi-channel valves for controlling soft robots. Three types of multi-channel-valve modular units (3/2 way valve, 4/2 way valve and 5/2 way valve) are designed to control the flow of pneumatic signals. A bistable modular unit with a pneumatically-driven bistable structure is used to take input from pneumatic signals to operate the attached multi-channel valve unit. A computing system can be made by attaching the desired multi-channel valve units to a certain number of bistable units. The computing system distributes the energy obtained from constant pressure resources to a multi-chamber soft robots to control its actuation, based on the pneumatic signal input.

magnetic resonance imaging). Another limitation is sensory information processing. In many applications, the conversion of pneumatic sensory information into an electrical signal before being processed back to a pneumatic signal for control brings additional system complexity and limits the application in extreme conditions.

These existing limitations make the development of electronic-free valves a critical contribution to the future of fully soft robots required in extreme environments. This encouraged many researchers to develop various soft or electronics-free devices to compute and regulate the pneumatic signal and power for soft robots. One typical work is a soft valve that makes use of a semi-spherical bistable structure and two pairs of kinking tubes [7]. This design uses a passive bi-stable membrane driven by external pressure to press and make the internal tubing buckle, therefore regulating the flow based on the input pneumatic signal. [8] also developed three different soft switch valves (a normally-open valve, a normally closed valve and a hysteretic valve) to control the locomotion of a soft crawler. These valves are made of soft tubes which are adhered to the skin of the robots. The linear deformation of the actuators is used to kink the tubes and therefore regulate the flow, while a bistable membrane provides the hysteresis. More recently, with the development of multi-material 3D printing technology, [9] designed a set of fully 3D printed fluidic circuit elements including fluidic diodes, "normally closed" valves, and "normally open" valves with tunable pressure-gain ranging from

0.67 to 2.

All those electronics-free valves described above are fundamentally 2/2 or 3/2 way valves with only two or three ports forming one single air channel and two corresponding states (blocked and unblocked). More valves are needed when the system requires multiple independent-controlled signals: a) one valve is used to control one single chamber gripper or one single chamber crawler [7]; (b)three valves are used to control the locomotion of a three-chamber crawler [8]; (c) three valves are used to control three independent fingers of a robotic hand [9]. (d) four valves are used to control the oscillating actuation of a two chamber soft turtle [9]. Soft robots developed from previous research have greatly demanded a pneumatic system that can regulate the airflow in multiple channels or chambers based on a single input signal. For example, the bi-directional actuator requires one chamber inflated and the other deflated [10]. A soft legged robot with a diagonal couplet gait pattern also requires opposite actuation for the two diagonal pairs of feet [11]. Suppose only traditional 2/2 way valves are implemented, complex pneumatic circuits have to be designed with many valves, which severely increases the overall size, weight, and power required for computation and system complexity.

An industrial solution to direct air from different sources to different chambers is the Directional Control Valve (DCV), which consists of a spool inside a cylinder to restrict/permit the air flow in different air channels [12]. However, these industrial valves' material, size, weight, and cost limit their applications in untethered electronics-free soft robots. More recently, the advance of additive manufacturing allows the design of 3D printed directional control valves [13]. However, the development is still in its infancy. According to the experiments, the use of single-material 3D printing brings inevitable leakage, resulting in at least 3% pressure loss [13]. This can be solved by introducing soft seals with a multi-material 3D printer.

Valves with multiple channels were also exploited from the microfluidics community. [14] designed a rotary planar bistable multi-port valve that successfully regulates the flow in 5 separate fluidic channels, yet incorporating a stepper motor that limits the size and overall weight of the system. The first electronics-free multi-channel valve successfully embedded in an untethered soft robot was designed by [11]. The valve in [7] was modified by adhering two (rather than one) fluid lines to either side of the bistable membrane so that the valve can be used as a 4/2 way valve. One limit of this work is the leakage brought by its kinking tube mechanism when the controlled chamber has a high operation pressure. The fabrication of the valve also requires significant manual work.

Thus, this paper presents a method for 3D printing modular multi-channel valves for complex pneumatic circuit design (Fig. 1). By rapid manufacturing soft bi-stable structures, the design of 3/2-way, 4/2-way, and 5/2-way valves are proposed to control multiple air channels in soft robots. These valves of 50 mm x 18 mm x 18 mm have a breakthrough pressure of 187.2 kPa and a flow rate of 7.42 L/min under 50 kPa pressure loss. Finite element method (FEM) is used to validate the design of the valve in terms of sealing performance. The modular approach to fast integrate multiple valves and to program advanced logical gates for multi-channel soft robots is demonstrated with a bi-directional soft robotic manipulator.

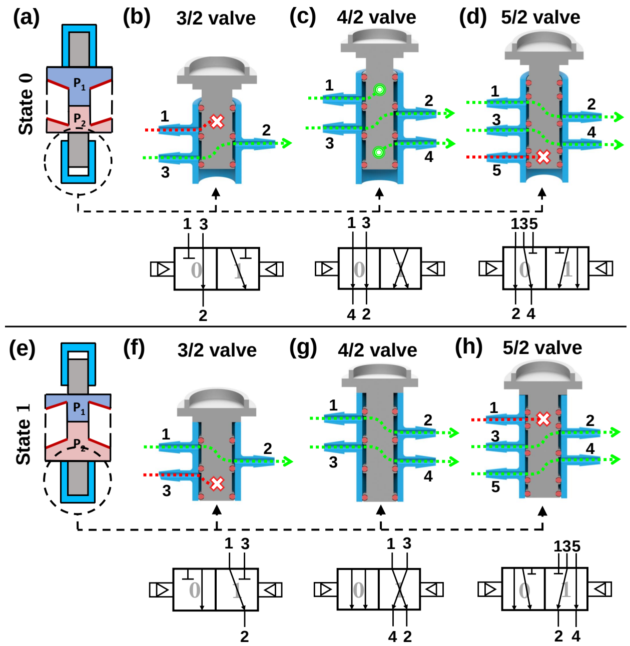

Fig. 2. Design and operating principles for 3D printed multi-channel valves. The overall structure of these valves is shown in **(a)** and **(e)**. All types of multi-channel valves include the same bistable modular unit in the middle. The structure consists of two symmetrically oriented bistable conical shells (shown by solid red lines). The two conical shells are tethered by unstretchable connectors (shown by black dotted lines) so that there's always one shell in "expanded" state and the other shell in "contracted" state. The state of the bistable structure can be switched between State I and State II by applying positive pressure to chamber P_1 or P_2. A spool with soft seals (shown in grey) is attached to each end of the central bistable structure and is placed in a cylinder (shown in blue), controlling the opening and closing of multiple air channels based on the state of the bistable structure. The 3/2, 4/2 and 5/2 way valve unit each comes with a unique spool and spool cylinder, with the geometry and working principle presented in **(b)** and **(f)**, **(c)** and **(g)**, **(d)** and **(h)**, respectively. The logical symbol of each valve at each state is placed below each corresponding spool and cylinder pair.

II. Design and Fabrication of the 3D Printed Directional Control Valve

A. Modular design of the multi-channel bistable valve

The operation of the valve makes use of a bistable structure to eliminate the need for a continuous signal. The bistability of the structure comes from two symmetrically oriented conical chambers (shown in Fig. 1). The states of the chamber can be switched from one state to another by applying a pneumatic signal (positive pressure) to one of the chambers. The state of the bistable structure determines the position of a spool in its cylinder, which has multiple spool seals distributed along its axial direction. The seals fit between the spool and the cylinder and prevent air from going through. This means that the space between the spool body and the cylinder is divided into multiple isolated regions so that different air channels can be restricted or permitted. By changing the location of each seal along with the spool and each port along with the cylinder, we designed a “3/2 way valve”, a “4/2 way valve,” and a “5/2 way valve” to suit different applications.“3”,“4” and “5” respectively indicates the total number of ports on the spool cylinder and the number “2” refers to the number of states of the valve.

Fig. 2 shows the switching stroke for the valves. The bistable “State 0” and “State 1” of the valve are shown in Fig. 2 (a) and (e). Once sufficient pressure is applied to the top shell P_1, the top shell will be switched to an “expanded” state. Due to the restricted length of the tether (black dashed line in Fig. 2(a)), only one shell can be in the “expanded” state at one time, which means the bottom shell will be pulled to its “contracted” state. To switch the valve back to “State 1”, a positive pressure is applied to the bottom chamber P_2. In “State 1”, the connection status of the controlled air channels in 3/2, 4/2 and 5/2 way valves are shown in Fig. 2(f)(g)(h). In “State 0”, the connection status of the controlled air channels in 3/2, 4/2 and 5/2 way valves are shown in Fig. 2(b)(c)(d). One should note that all ports, spools and the spool seals were placed on both sides of the valves in a symmetrical manner, therefore bringing the valves a completely symmetrical structure and behaviour. Fig. 2 only shows the air channels located inside the bottom of valves to ensure simplicity and ease of reading.

B. Fabrication

The use of a multi-material Polyjet 3D printer (J735, Stratasys Ltd, USA) allows both rigid and soft materials to be implemented in the design. The materials used by the printer are Vero© and Agilus30©. Vero is a rigid plastic-like material with a quoted tensile strength of 50-65MPa, a Young’s Modulus of 2200 MPa and a shore hardness of 83-86D. Agilus30 is a soft and rubber-like material, which has a quoted tensile strength of 2.1-2.6MPa, a Young’s Modulus of around 1MPa and a shore hardness of 30A (Stratasys Ltd.). The compliant conical shells (shown as solid red lines in Fig. 2(a)(e)) and the spool seals are printed by pure Agilus30. The support material used during printing is SUP 706 (J735, Stratasys Ltd, USA), which can be chemically removed by placing the printed components in a tank (GEMINI SSR-550) filled with chemical support removal solution (0.02 kg/L Sodium Hydroxide and 0.01 kg/L Sodium Metasilicate).

C. Finite Element Modelling of the channels

One key component in this design is the seals on the spool printed by compliant material, as it supposes to regulate the airflow into different ports with minimum leakage. Therefore, we performed FEA simulations to validate the spool design. The simulations were performed using COMSOL Multiphysics 5.6 (COMSOL Inc., Sweden). The CAD model of the spool and cylinder of the 3/2-way-valve unit was imported into COMSOL. Distinct material properties were then set to each material used by the design. Specifically, the spool seals were modeled as Agilus30 (E = 0.51 MPa;ρ = 1.15×10^3 kg/m^3; v = 0.49), while the spool body and cylinder were modeled as Vero (E = 2495 MPa; ρ = 1.18×10^3 kg/m^3; v = 0.375) [15]. Two simulations were implemented, whose procedures are as follows:

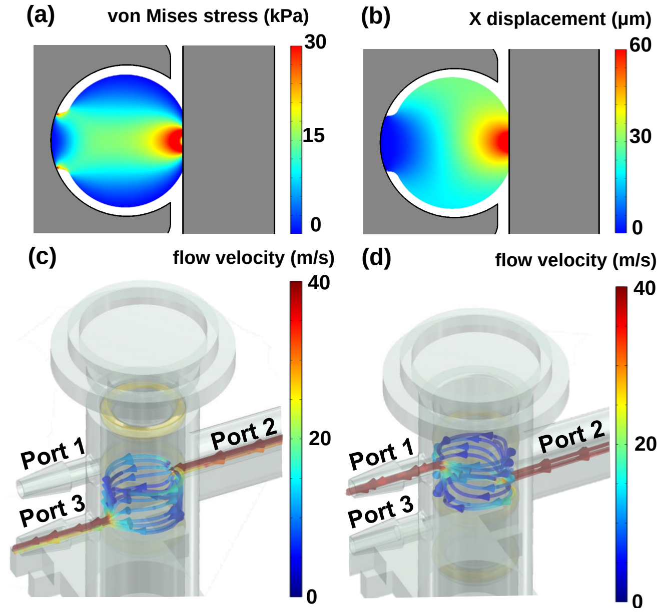

Fig. 3. FEM results of the multi-channel valve unit. **(a)** shows the stress distribution of the spool seal during operation. **(b)** shows the displacement distribution of the spool seal. The fluid dynamics simulation of the airflow in the valve under both states are presented in **(c)** and **(d)**.

The first simulation aims to find the deformation and stress distribution of the spool seal. This simulation is performed in a 2D manner using the COMSOL Multiphysics “Solid Mechanics” module with a “Stationary” study. The rigid spool body is assigned as a ”fixed” constraint, and a uniform boundary load is applied to the spool cylinder, therefore compressing the compliant piston seal. The boundary load is incrementally increased from zero until the inner surface of the spool cylinder reaches the actual fabricated diameter. “User-controlled mesh” calibrated for “General Physics” with a maximum element size of 0.02 mm is used for meshing. The obtained stress distribution and the deformation of the piston seal are presented in Fig. 3(a) and (b), respectively. Maximum von Mises stress within the seal is 28.7 kPa.The internal stress and deformed shape of the seal guarantees a seamless engagement between the spool seal and the cylinder, therefore eliminating the leakage. The second simulation aims to validate the value spool design for flow regulation and investigates the detailed flow pattern inside the valve. This simulation is performed in a 3D manner using the COMSOL Multiphysics “Single Phase Laminar Flow” module with a ”Stationary” study. Port 2 is set as an “inlet” with a pressure of 10 kPa, while and the other two ports are set as “outlet”. All other surfaces in the model are assigned as the ”wall” constraints. The material inside the valve air channel is modelled as air at room temperature. ”User-controlled mesh” calibrated for ”Fluid dynamics” with a predefined ”fine” element size is used for meshing. The

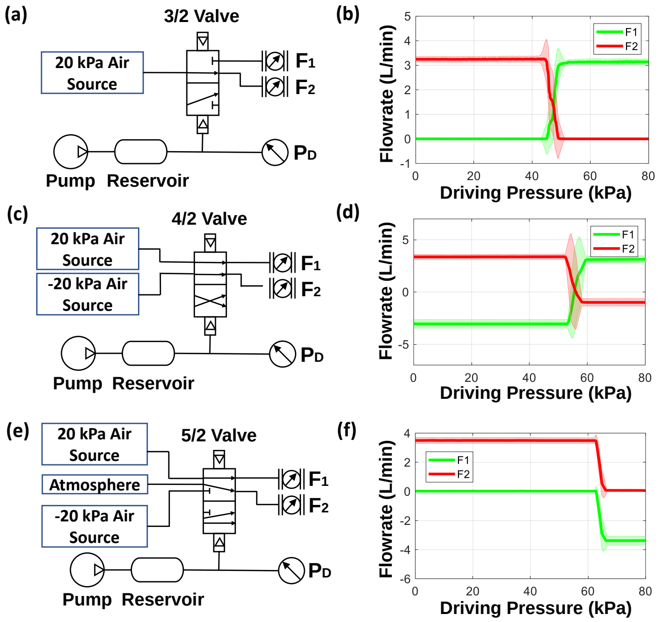

Fig. 4. **(a)**, **(c)**, and **(e)** show the experimental setup for measuring the switching behaviour of the 3/2 way, the 3/2 way, and the 5/2 way valve, respectively. P_D represents the driving pressure used to switch the state of the valve. The volume flow rate at both output ports are measured by flow rate sensor F_1 and F_2. **(b)**, **(d)**, and **(f)** show how the output flow rate changes as P_D increases through the 3/2 way, the 4/2 way, and the 5/2 way valve, respectively. The volume flow rate at all output ports are measured by flow rate sensor F_1 and F_2. The pressure applied at both input ports, P_{s1} and P_{s2}, are set to 20 kPa and -20 kPa respectively. The shaded errorbar represents the standard deviation of 5 independent trials.

obtained velocity field of the airflow under both State 0 and State 1 are presented in Fig. 3(c) and (d). The simulation shows that the flow rate is 1.68 L/min and 1.72 L/min for State 0 and 1, respectively, when the pressure loss across the valve is 10 kPa. The flow pattern in both State 0 and State 1 shows that the position of the spool in the cylinder successfully regulate the airflow as desired.

III. Experiments and Results

A. Switching behaviour of the valve

The valves designed in this work take a pneumatic signal as input to switch its state. The experiments presented in this section aims to investigate the performance of its switching behaviour. The experimental schematics and results are shown in Fig. 4.

As presented in Fig. 4(a)(c)(e), air sources with different constant pressure are connected to specific ports of the 3/2, 4/2 and 5/2 way valve, respectively. Each air source used consists of an air compressor (BB50D, BAMBI AIR COMPRESSORS LTD, with integrated reservoir), a pneumatic filter (AF20-F02-A, SMC) for contaminant removal and a pressure regulator (AR20-F02-1-B, SMC) for controlling the pressure applied to the valve ports. To continuously monitor the switching behaviour of the valve, flow rate sensors (HAF 20SLPM AIR, Honeywell) are connected in series to all other valve ports. The changes in the measured volume flow rate indicate the change in the valve state. The input pneumatic signal used to switch the state of the valve P_D is provided by a pneumatic system including a displacement pump (mini air pump, rated airflow of 2L/min, SIMILK), a solenoid valve for venting (VDW10AA, SMC), a pressure sensor (ADP5160, Panasonic) and a reservoir (rigid plastic, with the volume of 250 ml) for pressure stabilization. The valve driving pressure P_D is increased slowly from 0 to 80 kPa at a rate of 1 kPa/s through a PID controller. All sensory data are captured through Teensy 4.1, whose sampling rate is set at 5 kHz. The measurements were taken repeatedly 5 times with 0.5 hrs relaxation between each trial to get rid of any hysteresis effect and ensure all valves are measured in a consistent manner. The results are presented in Fig. 4(b)(d)(f). The switching behaviour consistency of this bistable structure under continuous operation (switching at 0.2 Hz) has been tested in our previous work [16].

As shown in Fig. 4(b)(d)(f), the measured flow rate curve demonstrates that all three valves successfully perform the desired function without "cross-talking" caused by the leakage. The critical pressure required for valve switching increases with the number of valve ports (48.6 kPa for 3/2 way valves, 55.5 kPa for 4/2 way valves and 65.4 kPa for 5/2 way valves). This is due to the increased friction between the piston and the piston cylinder as the number of piston seals goes up. In terms of consistency, the standard deviation in critical switching pressure between the 5 independent trials on the 3/2, 4/2 and 5/2 way valves are 2.1 kPa, 1.98 kPa and 1.4 kPa, respectively.

B. Valve flow rate Characterization

Volume flow rate plays a significant role in the performance of the valves, as it determines how fast the pneumatic actuators connected to them can be activated or deactivated. Therefore, the flow rate characterization experiments were implemented to determine the volume flow rate in each valve channel versus the pressure drop across the valve.

To do the characterization, we connected all channels in the valves to a variable-pressure source and measured 1) the volume flow rate through each valve channel; and 2) the pressure drop across the valve. The flow rate is measured by connecting a digital airflow sensor (HAF 20SLPM AIR, Honeywell) in series with the valve channel. The pressure drop across the valve is measured by placing two pressure sensors (ADP5160, Panasonic) at the upstream and downstream of the valve channel, respectively. Each valve comes with two states, so the characterization was implemented for all opening channels under both valve states. The measured flow rate versus pressure drop relationships were then used to fit the mathematical model stated by ISO 6358 [17] and used in the community [18] (see Equation 1 and 2). The experimental results and the fitted models were presented in Fig. 5 and Table I. The simulation results from CFD analysis

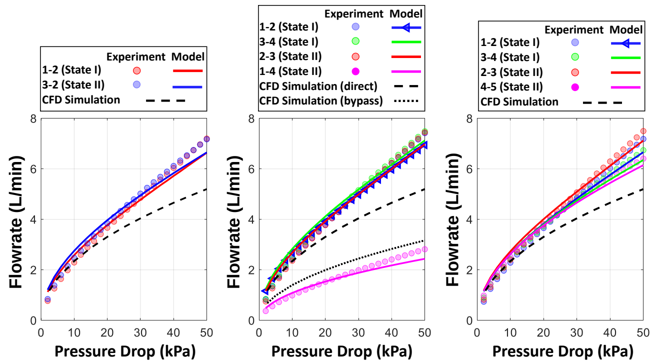

Fig. 5. Flow rate characterization of the air channels in the 3/2 way valves **(a)**, 4/2 way valves **(b)** and 5/2 way valves **(c)** under both of their states. CFD simulation results are presented for comparison. The experiment data are presented in circular dots, while the fitted models are presented in solid lines.

TABLE I

THE MEASURED SONIC CONDUCTANCE AND CRITICAL PRESSURE RATIO AT CHOKED POINT OF EACH CHANNEL OF THE VALVES UNDER BOTH STATES.

	Channel	C	b	
3/2 Valve	1-2 (I)	0.0450	0.355	*Sonic conductance C and critical pressure ratio at choked point b is presented. The unit of C is "lpm/kPa". The percentage deviation is obtained by dividing the standard deviation by the mean value of the corresponding quantities.
	3-2 (II)	0.0472	0.386	
	Deviation	3.37%	5.92%	
4/2 valve	Channel	C	b	
	1-2 (I)	0.0472	0.334	
	3-4 (I)	0.0480	0.391	
	2-3 (II)	0.0487	0.290	
	1-4 (II)	0.0163	0.548	
	Deviation	39.56%	28.84%	
5/2 valve	Channel	C	b	
	1-2 (I)	0.0457	0.354	
	3-4 (I)	0.0445	0.401	
	2-3 (II)	0.0498	0.286	
	4-5 (II)	0.0432	0.441	
	Deviation	6.23%	17.9%	

are also included for comparison.

$$Q = C\Psi P_{high} \tag{1}$$

$$\Psi = \begin{cases} \sqrt{1-(\frac{\frac{P_{Low}}{P_{High}}-b}{1-b})^2} & \frac{P_{low}}{P_{high}} \geq b \\ 1 & \frac{P_{low}}{P_{high}} < b \end{cases} \tag{2}$$

where Q is the volume flow rate inside the valve channel, P_{high} is the absolute pressure at the valve upstream, P_{low} is the absolute pressure at the valve downstream, C and b are the parameters which needs to be fitted and they represent sonic conductance and critical pressure ratio at choked point respectively.

It can be seen from Fig. 5 and Table I that most air channels come with similar flow rate characteristics as they share the same geometry and dimension. When these valves are applied in real soft robotic applications, the consistency in flow rate characteristics within each valve channel ensures consistent behaviour of the soft robots no matter which valve state is used. The average flowrate under 50 kPa pressure loss over all valve channels is 6.74 L/min. The maximum flowrate observed under 50 kPa is 7.42 L/min, measured at the "2-3 (STATE II)" channel in the 5/2 valve. The 3/2 way valve comes with the best consistency between its channels, with a percentage deviation of 3.37% and 2.92% in C and b respectively. The 5/2 way valve comes with a slightly lower consistency between its air channels, with a percentage difference of 6.23% and 17.9% in C and b respectively. The slight reduction in consistency is caused by the increased number of piston seals included in the design. One should note that the 4/2 way valve comes with a relatively poor consistency as the "1-4" channel in State II comes with a much lower flow conductance. This is because the special "bypass" geometry of this air channel significantly increases the overall length and geometrical complexity of the channel. The other three air channels in the 4/2 way valve come with a satisfying consistency with a percentage deviation of 1.6% and 15.0% in C and b respectively.

C. Breakthrough pressure when no energy supplied

Due to the bistability of the valve, no energy is required for maintaining either state of the valve. This experiment aims to find out how much pressure can be held in the valve channels without any external force or power applied. The experimental schematics is shown in Fig. 6(a). Three pressure sensors (ADP60, Panasonic) were placed at each port of the valve. A compressor with pneumatic filter and regulator is used to apply air with gradually increased pressure (called source pressure P_s) to the input port (port 2) of the valve. The breakthrough pressure is defined as the maximum pressure that can be held within the air channel without leakage. The specific algorithm for breakthrough pressure identification is shown in Fig. 6(b). "$P_2 > 0.01 \times P_s$" indicates that leakage results in some unwanted "cross-talking" between channels, while "$P_1 < 0.99 \times P_s$" indicates that the pressurized air leaks to the exterior environment. Since all valves designed in this work share the same piston seal design, only 3/2 way valve is investigated here. The experimental results are shown in Fig. 6(c). The measured breakthrough pressure of a newly fabricated valve is 187.2 kPa, with a standard derivation of 3.73 kPa among five independent trials. A fatigue test is preformed to investigate the long term reliability of the spool seals made of Agilus 30. The position of the spool in the spool cylinder is repeatedly switched, while the breakthrough pressure is measured throughout the process every 500 cycles until failure. To investigate whether the hardness of the spool seals affects the long-term reliability of the valve, the same fatigue test is also preformed on a valve whose spool seals are made of a less compliant material (FLX9760, Stratasys Ltd, USA, 60A shore hardness). As shown in Fig. 6(d), the Agilus 30 spool seals retain the optimal performance within the first 1000 cycles and show a 35.9 % drop in breakthrough pressure at 1500 cycles, while the less compliant spool seals degrade within less than 200 cycles and completely fail after 600 cycles.

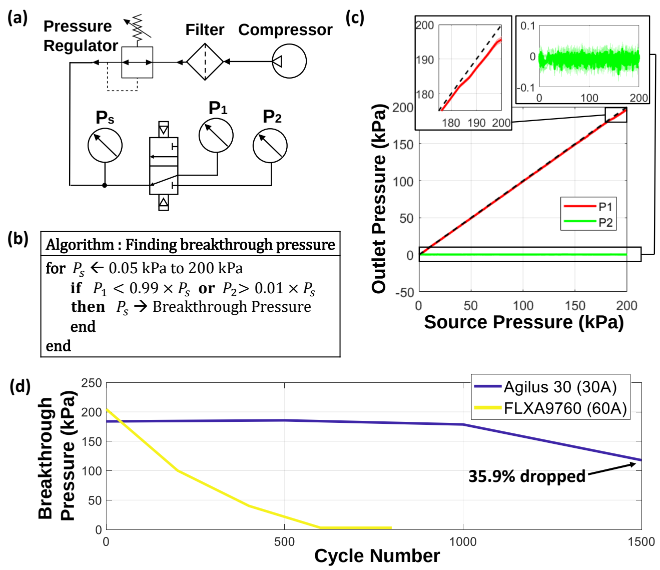

Fig. 6. **(a)** shows the experimental setup used to find the breakthrough pressure of the valve. P_s represents the source pressure applied to the inlet of the valve. P_1 and P_2 represent the measured pressure at the other two ports of the valve. The algorithm for breakthrough pressure identification is shown in **(b)**. The experiment results of the output pressure readings (P_1 and P_2) versus the source pressure P_s of a newly fabricated valve are shown in **(c)**. The long-term reliability of the spool seals with different shore hardness are presented in **(d)** in a fatigue test.

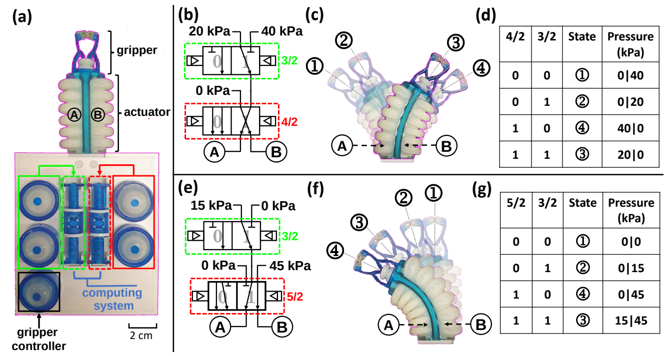

Fig. 7. **(a)** shows a bi-directional actuator with a gripper being controlled by an electronics-free control board consists of multi-channel valves. The computing system in the middle consists of two valves, while each of them switches its states based on the pneumatic signal sensed by the two 3D-printed pneumatic switches connected to it. A separate manual pneumatic switch is used to control the gripper. **(b)** shows the schematics when a 4/2 way valve and a 3/2 way valve is used to control the bi-directional actuators with two independent chambers. Chamber A and B refers to the two independent chambers in the bi-directional actuator. **(c)** shows all possible configurations, which can be achieved by switching the states of the valves. **(d)** shows the truth table, which describes the relationship between the valve state and each corresponding configuration. **(e)** shows the schematics when a 5/2 way valve and a 3/2 way valve is used to control the bi-directional actuators with two independent chambers. **(f)** shows all possible configurations, which can be achieved by switching the states of the valves. **(g)** shows the truth table, which describes the relationship between the valve state and each corresponding configuration.

D. Controlling a bi-directional actuator

The modular approach of the valve design allows multiple channels to be connected to achieve diverse logical computation. To demonstrate the modularity, the multi-channel valves were used to control a bi-directional actuator (see Fig. 7(a)). The bi-directional actuator consists of two air chambers with side bellows (Ⓐ and Ⓑ). Two different control schemes were used: (1) "3/2 way valve + 4/2 way valve" and; (2) "3/2 way valve + 5/2 way valve". Four 3D printed manual switch controller were used to generate the pneumatic signal so that they can switch the state of the two valves based on manual operation. The schematics of the pneumatic circuits under both control schemes are presented in Fig. 7(b) and Fig. 7(e), respectively. Note that the constant pressure source used here is the same as the one used in Sec. III-A and Sec. III-C. A pneumatic driven gripper is attached to the tip of the bi-directional actuator to perform a demonstration of manipulation, attached in the supplementary video.

As shown in Fig. 7(c), the "3/2 way valve + 4/2 way valve" control scheme successfully controls the bi-directional actuator through four different postures located symmetrically in both directions. The measured bending angles are -54^o, -34^o, 36^o and 60^o. The slight difference between leftward and rightward bending angles are due to the small stiffness difference between the left and right chamber (manufacture error). As shown in Fig. 7(f), the "3/2 way valve + 5/2 way valve" control scheme behaves like a 2 bit Digital-Analogue Converter (DAC), controlling the bi-directional actuator through four different amount of bending in one direction. The measured bending angles are 0^o, 17^o, 43^o and 64^o.The two truth tables which state the relationship between the valve status and the actuator posture are shown in Fig. 7(d) and (g).

IV. Discussion

The multi-channel valves designed in this work come with several key features which are highly beneficial when applied with soft robots, including (a) high breakthrough pressure; (b) low mass and; (c) multi-channel compatibility.

Thanks to the multi-material 3D printing technique, the soft spool seals can be directly printed on the spool without any post-processing or manual assembly. Meanwhile, the accuracy of the printer guarantees precise control on the optimal fit between the spool seal and the cylinder. These advantages bring this multi-channel valve design a much higher breakthrough pressure (187.2 kPa) compared with other electronics-free valves used in soft robotics, such as soft kink valves (63.0 kPa) [7], [19], [11] and 3D printed fluidic circuitry (at least 10 kPa pressure required by the valve to regulate a 20kPa source pressure) [9]. The high breakthrough pressure means the valves are compatible with a broader range of soft robots, which require higher pressure during operation [20]. Meanwhile, the ability to regulate high-pressure pneumatic signal enables the valve to deliver a higher range of pressure gain (the pressure ratio between the output pneumatic signal and the input pneumatic signal). The benefits brought by the high pressure-gain has been demonstrated in [11], where a small pneumatic signal induced by

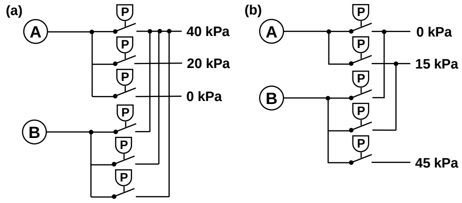

Fig. 8. The control scheme used to achieve the same functionalities as demonstrated in Fig. 7 by using only 2/2 approach. **(a)** shows the scheme for controlling the bi-directional actuator through four different postures at both bending directions (see Fig. 7(c)). **(b)** shows the scheme for controlling the bi-directional actuator through four different postures at single bending direction (see Fig. 7(f)).

a tactile sensor is sufficient to switch the state of a bistable valve, and therefore changing the locomotion direction of a soft legged robot. The mass of the multi-channel valve designed in this work is 5.4 g for 3/2 way valve, 6.1 g for the 4/2 way, and 6.3 g for the 5/2 way valve. This is 20 times lighter than the conventional rigid solenoid valves and 3-4 times lighter than the silicone-casted bistable valves [7]. The lightweight and electronics-free features of the valve enable it to be easily embedded in untethered soft robots without significantly increasing their mass or decreasing their mobility.

The valves designed in this work can control multiple independent air channels simultaneously, which can greatly reduce the number of valves used in the control circuit, especially when controlling soft robots with more than one air chamber. By using the "3/2 + 5/2 way valve" control scheme (see Fig. 7(e)(f)(g)), we successfully control the posture of the bi-directional actuator in a 2-bit DAC manner by using only two valves and two constant pressure sources. To achieve these postures with only 2/2 way valve, at least 5 valves must be used, while every valve requires an independent pneumatic signal (see Fig. 8(b)). In previous work [21], a similar 2-bit DAC operation make use of 12 valves and 4 constant pressure sources. By using the "3/2 + 4/2 way valve" control scheme (see Fig. 7(b)(c)(d)), we successfully control the posture of a two-chamber bi-directional actuator through four different configurations (two different bending directions with two different amplitudes). To achieve these postures with only 2/2 way valve, at least 6 valves must be used (see Fig. 8(a)). The valve number reduction brought by the multi-channel valves reduces the size and mass of the overall computing circuit and reduces the energy consumed by computing. Both of them are of great importance for soft robotic applications.

V. Conclusion

This paper presents a modular approach to design multi-channel bistable valves for pneumatically driven soft robots based on Multi-material 3D printing. Each valve comes with a bistable modular unit, which uses pneumatic signals to change its state. Different multi-channel-valve modular units (3/2 way, 4/2 way, and 5/2 way) are designed to provide varieties in the pneumatic circuit design. Each multi-channel-valve unit consists of a spool with multiple seals and a cylinder with multiple ports, therefore permitting and restricting the airflow in different air channels based on the state of the bistable unit. An FE simulation is performed to validate the design of the spool seals. The experiment characterization verifies that the proposed multi-channel valves successfully perform the desired function. The state of the valve can be switched by a pneumatic signal ranging from 48.6 kPa to 65.4 kPa, depending on the multi-channel valve units chosen. The valve can withstand a pressure of 187.2 kPa in the controlled air channels without leakage. The air channels in the multi-channel-valve units come with an average sonic conductance of 0.0436 lpm/kPa and an average critical pressure ratio of 0.379. With different multi-channel-valve units chosen, a dual-chamber bi-directional actuator can be controlled through different sets of computing system configurations.

Overall, the following features of this modular multi-channel valve design make it suitable for soft robotic applications. (1) The high breakthrough pressure of the valve ensures its compatibility with high-pressure soft actuators. (2) A higher range of pressure-gain. (3) A much lighter weight compared with conventional solenoid valves or other electronics valves in previous work. (4) The valves' multi-channel design significantly reduces the number of valve units required when controlling multi-chamber soft robots. The valve number reduction brings a decrease in system size and mass and reduces the energy consumed by computing. For future work, the valves can be used in an oscillatory circuit to achieve gait control for a soft-legged robot with multiple chambers. Size miniaturization can also be investigated further.

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