Electronic Supplementary Material (ESI) for Soft Matter.

SUPPLEMENTARY DATA

Title
A Fluidic Demultiplexer for Controlling Large Arrays of Soft Actuators

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Abstract
The field of soft robotics endeavors to create robots that are mostly, if not entirely, soft. While there have been significant advances in both soft actuators and soft sensors, there has been relatively little work done in the development of soft control systems. This work proposes a soft microfluidic demultiplexer as a potential control system for soft robotics. Demultiplexers enable the control of many outputs with just a few inputs, increasing a soft robot's complexity while minimizing its reliance on external valves and other off-board components. The demultiplexer in this work improves upon earlier microfluidic demultiplexers with its nearly two-fold reduction of inputs, a design feature that simplifies control and increases efficiency. Additionally, the demultiplexer in this work is designed to accommodate the high pressures and flow rates that soft robotics demands. The demultiplexer is characterized from the level of individual valves to full system parameters, and its functionality is demonstrated by controlling an array of individually addressable soft actuators.

Valve Characterization

We investigated the effect of five variables on valve closure: control pressure (P_c), flow pressure (P_f), control channel width (w_c), flow channel width (w_f), and membrane thickness (m). We made a set of 25 valves by fabricating five flow channels and five control channels which were bonded together. We repeated this process for four different membrane thicknesses, yielding a total of 100 valves. Each valve was tested at five operating points (P_f = 20, 40, 60, 80, or 100 kPa), resulting in 500 distinct data points of valve characterization data. To test a valve, we first pressurized a flow channel to one of the five operating points. The output of the flow channel was connected to a tube submerged underwater, so that bubbles were produced. We then gradually increased the pressure in the control channel until the bubbles stopped completely, indicating full valve closure.

We fabricated valves by bonding a flow layer (which defines the flow channels) to a control layer (which defines the control channels, and the membrane between the flow and control channels). This two layer laminate was subsequently bonded to a base layer (See Fig. S3A for a schematic). The flow layer molds were 3D-printed on an Objet30 Scholar 3D printer (Stratasys Ltd.) using either VeroWhite or VeroBlue material. The flow channels were designed to have widths of 600, 700, 800, 900, and 1000 µm, and heights equal to 25% of their widths. In practice, due to imperfections of the printer, actual flow channel widths were 748, 842, 906, 982, and 1114 µm. The cross-sectional shape of channels fabricated using this method is described in our earlier publication.[44] After printing, the molds were mechanically cleaned of support material and baked at 90°C for at least 24 hours. We used soft lithography to fabricate the control layer molds. We used 3 inch, <1 0 0>, virgin test grade, boron doped, p-type silicon wafers (ID: 447, University Wafer) as the substrate. For a target channel height of 55 µm we used SU-8 3050 (MicroChem Corp.) spin-coated at 3000 rpm that was exposed with a SkyRay 800 UV3805 Flood Curing System (Uvitron International). We treated the silicon wafers with silane (trichloro(1H, 1H, 2H, 2H-perfluorooctyl)silane, Sigma-Aldrich) vapor in a dessicator to inhibit adhesion between the elastomer and the wafer. Control channels were also designed to have widths of 600, 700, 800, 900, and 1000 µm, but in practice had widths of 634, 732, 851, 939, and 1030 µm. The base layer was fabricated by simply pouring elastomer on a silanized silicon wafer that had not been patterned via the soft lithography process.

The flow layer was made of Sylgard 184 (Dow Corning) that was mixed in the standard 10:1 ratio and degassed before being poured into the 3D-printed mold. The control layer was made of MED4-4220 (NuSil Technology) mixed in the standard 1:1 ratio (with an added solvent (OS-2 Silicone Cleaner and Surface Prep Solvent (Dow Corning)) equal to 20% of the elastomer weight). The control layer was degassed and spin-coated at either 500, 600, 800, or 1000 rpm for 100 seconds, yielding membrane thicknesses of 112, 105, 77, or 54 µm, respectively. The base layer was made of Sylgard 184 in the same manner as the flow layer. All elastomers were cured at 60°C for a minimum of four hours. We adhered the layers of elastomer through oxygen plasma bonding at 0.4 mbar and 35 watts for 30 seconds, ensuring that the relative humidity of the room was below 50%. Newly bonded elastomers were placed on a hot plate set to 100°C for 2–4 minutes.

Scaling Considerations

The appropriate channel widths for a given application are largely driven by actuator requirements. The target application determines actuator sizing (actuation force and speed). Actuator sizing determines the driving pressure and flow rate for the system (i.e., the pressure and flow rate of the *F* channels). Flow rate is a function of channel cross-sectional area. For a fixed channel shape (flow channel shape is discussed in our prior publication[44]), flow rate is a function of channel width. Flow channel width determines control channel width, based on the achievable pressure differential (see Fig. 2C of the main text).

Valve Design Considerations

The valves described in this work do not feature "gain". That is, a control channel of a given pressure is only able to close a flow channel of a lower pressure. Due to this design decision, circuit elements cannot be cascaded indefinitely, as the lowest level control pressure would eventually become prohibitively high.

Regarding the decision of whether to use push-up or push-down valves, the main text states that other have shown push-up valves are preferable under certain configuration assumptions.[43] Specifically, earlier publications describe a system that uses a glass substrate. In the push-up configuration, the effect of substrate material on valve performance should be minimal; for a given pressure in the control channel, the force on the membrane will be the same regardless of the substrate material. In the push-down configuration, the substrate material may have a non-negligible effect on valve performance. However, the primary influence (from material considerations) on valve behavior is the *relative* compliance of the membrane material compared to the substrate material. In this regard, the system presented here is analogous to the system presented in earlier work.[43] In that system, a relatively soft membrane (PDMS) interacts with a relatively hard substrate (glass). In our system, a relatively soft membrane (MED4-4220) interacts with a relatively hard substrate (Sylgard 184). In both systems, the membrane material is significantly more compliant than the substrate material.

Demultiplexer Fabrication

The demultiplexer described in the section of the main text titled "Demultiplexer" (and described in Fig. 1B, as well as Movie S1) was fabricated in an analogous manner to the valves described in the previous section, but with different flow and control layer designs. Flow channels were designed to be 1000 μm wide, but in practice were 1217 μm wide. Control channels were designed to be 200 μm wide (when not part of a valve) and 1000 μm wide (when part of a valve). Control layers were spin-coated at 600 rpm (in the same manner as described above), yielding membranes that were 105 μm thick.

Actuator Fabrication

As mentioned in the section of the main text titled "Actuator Design and Fabrication", a tri-chambered actuator was fabricated by dip-coating a set of three pins (1/16 inch diameter) into rubber (Elastosil M 4601, Wacker Chemie AG). The pins were press-fit into a hole in the elastomer that intersects one of the flow channels. The holes were punched manually with a 14 gauge needle with the aid of an acrylic alignment fixture wetted to the top of the elastomer. The pins were manually pressed through the holes in the elastomer and into a second acrylic fixture underneath the elastomer, which served to constrain the pins in a vertical position for the dip-coating process. After the dip-coating process was completed and rubber was cured on the pins and the top surface of the elastomer, the pins were removed through the bottom of the elastomer.

The spacing between the three pins is an important variable to consider when designing tri-chambered actuators for dip-coating. Tighter spacing leverages surface tension to counter gravity forces and holds rubber between the pins as it cures. The rubber trapped between the pins bridges the walls of the three chambers together into a single tri-chambered actuator. When the sets of pins are more closely spaced, fewer dips are needs to completely cover and connect the pin triplets. However, tighter spacing also increase the likelihood of cross-talk or leaking between chambers. This leaking is frequently caused by bubbles caught between the pins or weakened bonding to the surface of the elastomer due to the minimal area of material between the pins. Wider spacing between pins, conversely, minimizes the likelihood of leaking but the larger central gap creates wider overall actuators, which are stiffer and thus more difficult to bend. The larger gap also requires more dips to fill, resulting in thicker chamber walls that demand a higher pressure to induce bending. We opted for a 3 mm center-to-center spacing of pins to prevent cross-talk failure modes while maintaining low actuation pressures, and used this spacing as the standard in each of the tri-chambered actuators presented in this work. Although the fabrication procedure was largely, there was observable variation in actuator performance. An analysis of the statistical variation of actuator performance based on different fabrication parameters was performed in another study.[50]

Many variations of this recipe will produce successful actuators, but the following steps were used to create the actuator array described in the section of the main text titled "Integrated Demultiplexer and Soft Actuator Array" (and described in Fig. 4, as well as Movie S3). After pressing all pins into the demultiplexer, the tips of the pins were dipped into liquid rubber and then hung upside-down to cure. This curing orientation ensured that thin spots did not develop on the tip of the pins as a result of surface tension and gravity. This first tip coating step was followed by a dip over the full length of the pins, which were subsequently left to cure in their standard configuration (i.e., not upside-down). This coating step resulted in pins that were coated but not bridged. Cotton twine soaked in liquid rubber was then inserted between the sets of pins, ensuring that liquid rubber wetted to the interior edge of each pin to avoid gaps. The cotton twine was allowed to cure again with the pins pointing upward. A final dip was added over all of the pins and left to cure with the pins pointing downward.

Various modifications can be made to the dip-coating process to adjust the resulting performance of soft actuators. Changing the number of dip coating layers added directly affects the thickness of the chambers and thus the actuation pressure. With the process described above, the actuators integrated with the demultiplexer had an actuation pressure of 90 kPa. By changing the number of layers added, we have been able to make the dip-coated actuators functional over an operational pressure range of 7 – 344 kPa.

Design Details for Demonstration of Integrated System

The demultiplexer described in the section of the main text titled “Integrated Demultiplexer and Soft Actuator Array” (and described in Fig. 4, as well as Movie S3) was fabricated in a slightly different manner than the devices used for valve characterization or the earlier demultiplexer (described in Movie S1). Rather than being composed of a flow layer (which defines the flow channels), a control layer (which defines the control channels and the membrane), and a base layer (which serves as a backing to the control channels), this demultiplexer was composed of a flow layer (which similarly defines the flow channels), a membrane layer (which defines only the membrane), and a control layer (which defines the control channels). (See Fig. S3B for a schematic.) Both the flow and control layers were made from 3D-printed molds fabricated in the same manner as described above. The membrane layer was spin-coated onto a 100 mm silanized silicon wafer (ID: 452, University Wafer). The three layers were again bonded using oxygen plasma treatment. Both the flow layer and the control layer were fabricated from Sylgard 184, while the membrane layer was fabricated from MED4-4220.

In this demonstration, flow channels were designed to be 1000 µm wide, but in practice were 1217 µm wide. Control channels were designed to be 200 µm wide (when not part of a valve) and 1000 µm wide (when part of a valve), but in practice were 594 and 1338 µm, respectively. Thus, when not part of a valve, $w_c - w_f = -623$ µm, and $w_c - w_f = 121$ µm when part of a valve. With operating pressures of $P_F = 90$ kPa, $P_{PC} = 105$ kPa, and $P_{SC} = 120$ kPa, we have $P_c - P_f =$ 15 kPa or 30 kPa (based on whether the flow channel in question is connected to *F* or *PC*, and whether the control channel in question is connected to *SC* or *PC*). With a membrane thickness of 67 µm (achieved by spin-coating elastomer on a blank wafer at 1000 rpm), we would expect (based on Fig. 2C) that for $w_c - w_f = 121$ µm (i.e., when part of a valve), $P_c - P_f = 15$ kPa or 30 kPa would be sufficient to close the valve. Similarly, we would expect (based on Fig. 2C) that for $w_c - w_f = -623$ µm (i.e., when not part of a valve), $P_c - P_f = 15$ kPa or 30 kPa would be insufficient to close the valve. Indeed, this is what we found in the demonstration, corroborating the results of the valve characterization.

Demultiplexer Design and Operation

In the section of the main text titled “Demultiplexer”, we report that the number of inputs required to control *n* outputs is just log_2n+2. The number of inputs could be reduced further to log_2n+1 with the use of a “pressure divider”, which may be understood as a pneumatic voltage divider. That is, *F* and *PC* could be connected to a single pressure source through appropriately resistive channels. Tuning the values of the pneumatic resistors connecting *F* and *PC* to this single source would tune the values of P_F and P_{PC}.

To avoid situations in which a portion of the demultiplexer retains unwanted pressurization, a standard order of pressurizing the different inputs is followed. (1) First, we pressurize the desired *SC* inputs. (2) Second, we pressurize the *PC* input. (3) Third, we pressurize the *F* input. At this point, the selected output (O_0-O_8, based on the state of the input vector [SC_0 SC_1 SC_2]) will inflate. To deflate, the order is reversed: (4) First, we vent the *F* input. (5) Second, we vent the *PC* input. (6) Third, we vent the *SC* inputs. It should be noted that each input includes a three way valve that connects the channel in question to either the pressure source, or atmospheric pressure. In this way, any residual, unwanted pressurization within the system is avoided. It should be noted that such an actuation strategy enables operation even in a perfectly sealed system. That is, this design architecture does not rely on small leaks (e.g., pneumatic pulldown resistors) to slowly vent the actuators. Rather, the system is actively vented, providing much faster transitions from one state to the next.

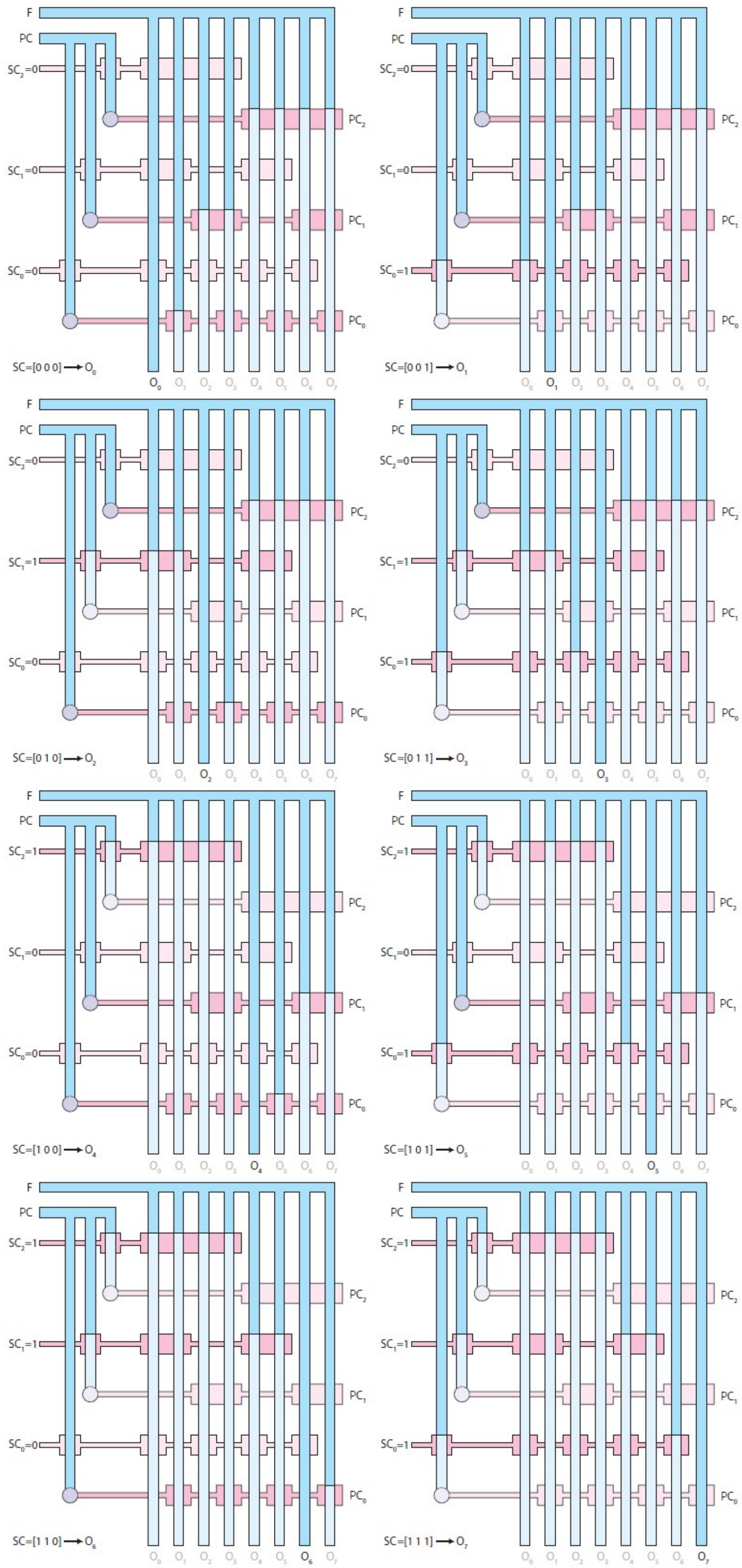

Figure S1: All possible outputs of the demultiplexer presented in Fig. 1B. *F*: Flow, *PC*: Primary Control, *SC*: Secondary Control, *O*: Output.

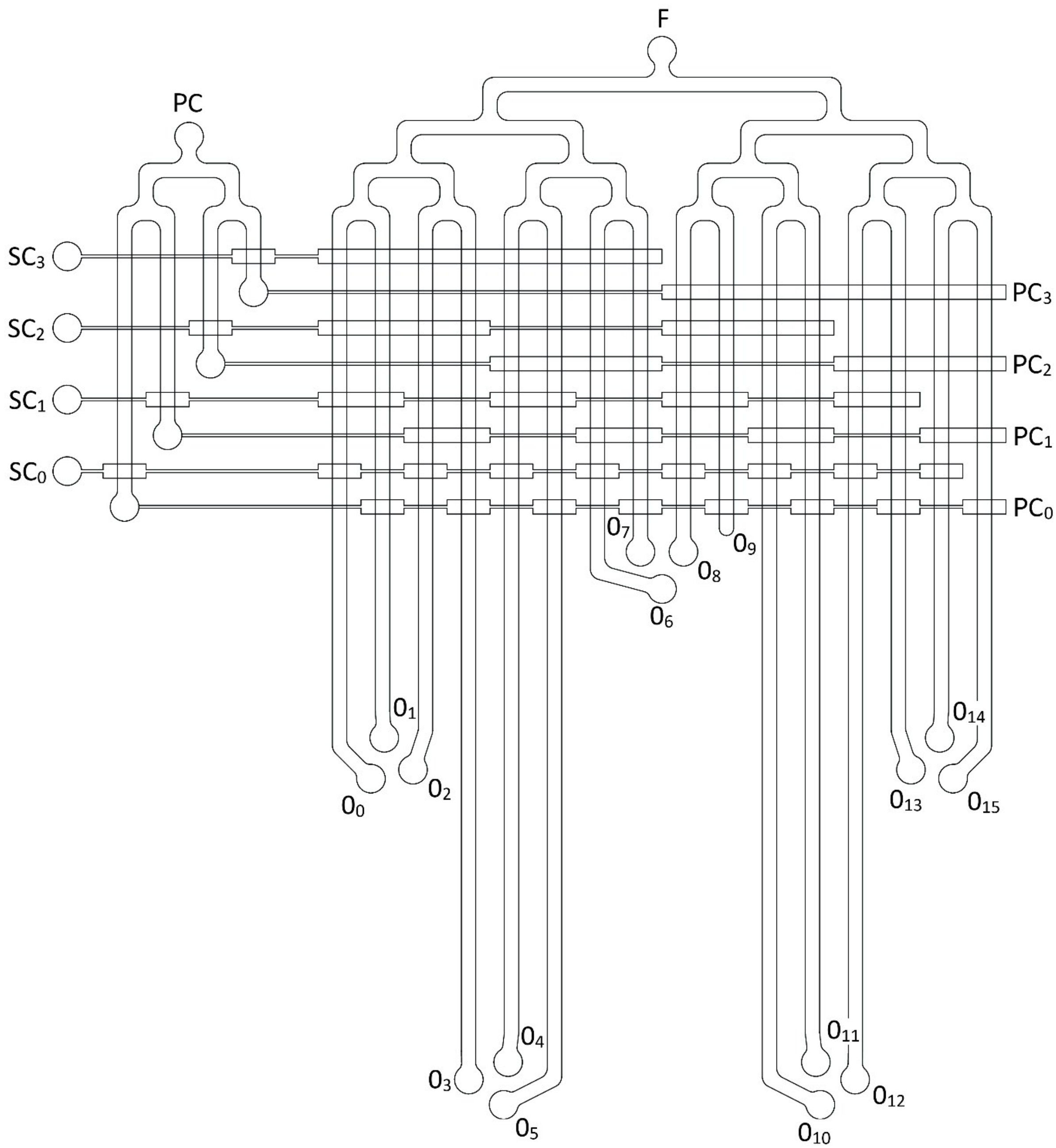

Figure S2: Microchannel routing of the flow and control layers for the demonstration described in the section of the main text titled “Integrated Demultiplexer and Soft Actuator Array”.

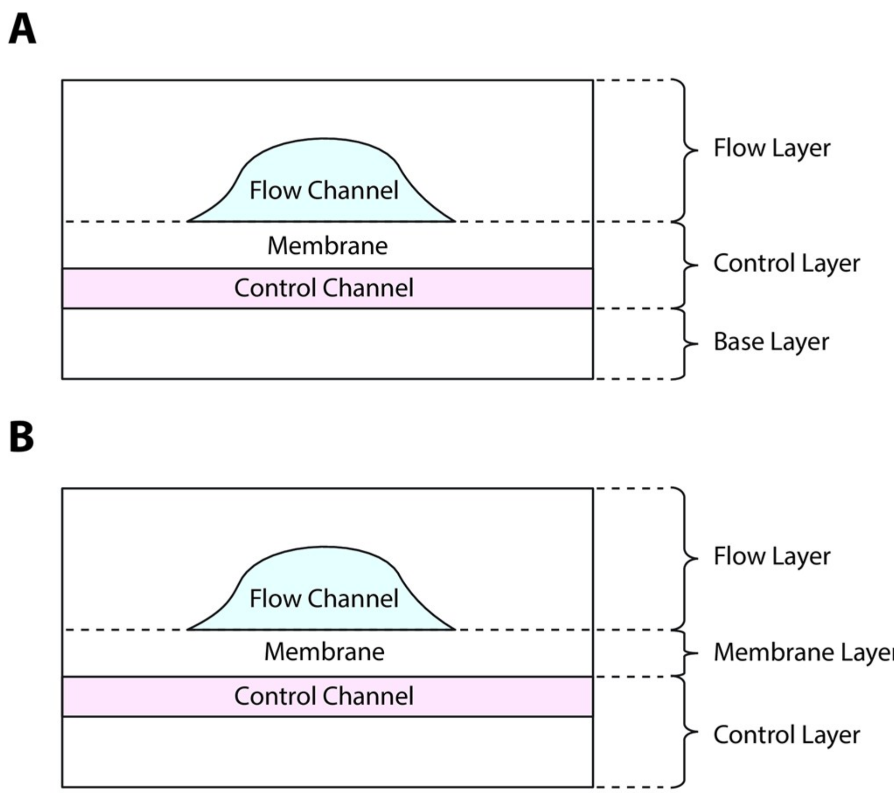

Figure S3: Layer definitions and details for **(A)** valve characterization and standalone demultiplexer, and **(B)** integrated demultiplexer and soft actuator array.

Movie Captions

Movie S1: Operation of a 3 Input, 8 Output Demultiplexer. In this movie, we show all possible states of the demultiplexer presented in Fig. 1B in the main text. A single pneumatic line (tubing with no tape) branches and connects to the inputs of three 3-way valves, which define the Secondary Control inputs to the demultiplexer (which can be toggled between atmospheric pressure and P_{SC} = 170 kPa). A second pneumatic line (tubing with red tape) connects to the Primary Control input of the demultiplexer (at pressure P_{PC} = 100 kPa). A final pneumatic line (tubing with yellow tape) connects to the Flow input of the demultiplexer (at a pressure of P_F = 30 kPa). The eight outputs ($O_0 – O_7$) are connected to tubing that is submerged under water, so that the selected output can be detected visually through bubbling. By toggling the three inputs, we are able to successfully address all eight outputs individually.

Movie S2: Operation of a Tri-Chambered Pneumatic Bending Actuator. Here we demonstrate the bending modes of a typical tri-chambered pneumatic bending actuator. The actuator was fabricated in the same method described in the section of the supplemental information titled “Actuator Fabrication”. There is no demultiplexer in this demonstration; rather, the three chambers are directly connected to three microfluidic channels which then interface with pneumatic tubing. By modulating the pressures in the three chambers, we can cause the actuator to bend in any desired direction. It should be noted that, when connected to a demultiplexer, only one chamber can be addressed at a time, permitting bending of the actuator in just three distinct directions.

Movie S3: Actuation of an Individually Addressable 15 Degree-of-Freedom Soft Actuator Array. In this movie, we show the operation of a 15 degree-of-freedom array of five tri-chambered actuators. By toggling the states of the four secondary inputs, we achieve actuation of all degrees-of-freedom. We first show a clockwise traveling wave, followed by a counter clockwise traveling wave, and end by showing a sequence of radial bends. In this demonstration, P_F = 90 kPa, P_{PC} = 105 kPa, and P_{SC} = 120 kPa. Both the isometric and top-down views are of the same trial. A schematic of the channel routing can be seen in Fig. S2.