Additional Pneumatic Logic Systems for Selectively Operating Distributed Pneumatic Elements*

Rafael Ferrin Pozuelo[1,2], Kohji Tomita[2] and Akiya Kamimura[2]

Abstract – An emerging application of microfluidic or pneumatic logic systems in soft robotics is the access to multiple tethered pneumatic elements through a reduced number of pneumatic lines. At the full paper "Pneumatic Logic Systems for Selectively Operating Distributed Pneumatic Elements" presented simultaneously at ICRA2025, we demonstrated two pneumatic logic systems capable of selecting a set of pneumatic elements in a distributed network and operating all the elements of the set simultaneously and independently through the available pneumatic lines. At this complementary work we summarize the working principles and propose alternative valves, improved activation processes and two additional circuit designs: A long linear network with shorter selection sequences and a non-hierarchical network triggered by structured selection sequences.

Index Terms – Microfluidics, pneumatic demultiplexer, pneumatic logic, soft robotics.

I. Introduction

Consider a lunar base equipped with a range of pneumatic systems, including inflatable and orientable structures for solar panels or antennas, pneumatic doors, distributed sensors (such as air pressure and door status indicators), external inflatable robotic arms for inspection and maintenance, as well as tethered heavy-duty robots equipped with pneumatic tools for mining, cargo handling, construction, and other operations.

Some of these devices benefit from the coordinated operation and communications enabled by electronic systems, while others can be efficiently controlled sequentially by a simple and hence robust pneumatic logic system.

Even devices controlled by electronic systems benefit from an auxiliary pneumatic control system, which provides a backup in the event of electronic malfunctions caused, for example, by radiation or an electromagnetic pulse.

Two of these pneumatic logic systems were presented in a full paper at ICRA2025, available in the conference proceedings, including a glossary of terms used in this work .

Compared to prior state-of-the-art systems [1], [2], [3], [4], [5], [6], [7], our approach offers the advantage of operating over a distributed network. The main drawback, however, is the increased selection time required to access each actuator. As a trade-off, they can address an unlimited number of actuators without the need for additional pneumatic lines.

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II. Components and Working Principles

To design a sequential selection system for controlling multiple distributed or tethered pneumatic elements, the first step is to identify which elements require multiple pneumatic lines for operation and which groups of elements must be actuated simultaneously and independently. Based on this, the required number of independently controlled lines, referred to as input lines, is deployed throughout the system.

The pneumatic elements are then organized into distinct sets, with the elements in each set connected to the input lines via a normally closed pneumatic valve, referred to as an activation valve, that includes a separate channel for each input line. This system architecture illustrated in Fig. 1a. When an activation valve opens, it connects its corresponding set of elements to the input lines, allowing those elements to be actuated simultaneously and independently.

An additional pneumatic line, referred to as the enable line, is deployed to actuate the activation valves using enable pressure. To determine which activation valve receives enable pressure, selection valves and blocking valves are installed along the enable line (Fig. 1b). Each selection valve is connected to one of the input lines and acts as a barrier that opens in response to low-pressure pulses on that input line. After the pulse, it closes again unless it has enable pressure upstream, in which case it remains open until enable pressure is removed. Blocking valves also serve as barriers, but they are initially unlocked. When one of their inputs receives enable pressure, they latch and block the other input until enable pressure is removed. As a result, a sequence of pulses

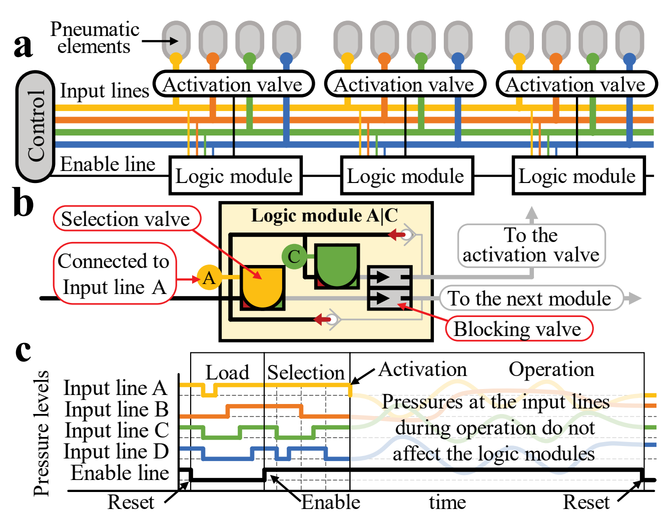

Fig. 1. Pneumatic sequential selection systems. **(a)** Diagram showcasing the common components. **(b)** Example of a logic module composed by selection and blocking valves. **(b)** Example of the operating cycle.

on the input lines can be used to redirect enable pressure to a specific activation valve while blocking the paths to all others. Once the selection is complete, the path cannot be altered by further pulses in the input lines, making it possible to repurpose the input lines for operating the pneumatic elements after the activation valve opens. The selected path is maintained entirely by enable pressure, and removing it effectively resets the system. Fig. 1c shows an example of an operating cycle.

III. Alternative Types of Valves

In our prototypes we use set-reset valves introduced in our previous paper at this conference, but similar logic circuits can be implemented using other types of valves, making the system compatible with various manufacturing technologies.

For the selection valves, the required behavior is detailed at Fig. 2a, from left to right: they must be able to close with high pressure in the input line (control) when the enable line (flow) is at low pressure, remain closed with the same high pressure even when enable pressure is present, and open only when a low-pressure pulse is applied to the input line, latching open as long as enable pressure persists. This functionality can be implemented using different types of normally open valves. The advantage of using set-reset valves is that they can remain latched open even under significant pressure drops in the enable line (labeled as flow DROP in Fig. 2a).

However, similar latching behavior can also be achieved by interlocking two standard normally open valves, as shown in Fig. 2b. This interlocking strategy can also be applied to implement the blocking valves, which require symmetric latching behavior: latching open the first input that receives enable pressure and blocking the opposite input as long as enable pressure persists.

a **Flow**	LOW	LOW	HIGH	HIGH	HIGH	DROP
Control	LOW	HIGH	HIGH	LOW	HIGH	HIGH
Output	OPEN	CLOSED	CLOSED	OPEN	OPEN	OPEN
Action	Opens	Closes	Resists	Opens	Does not close	

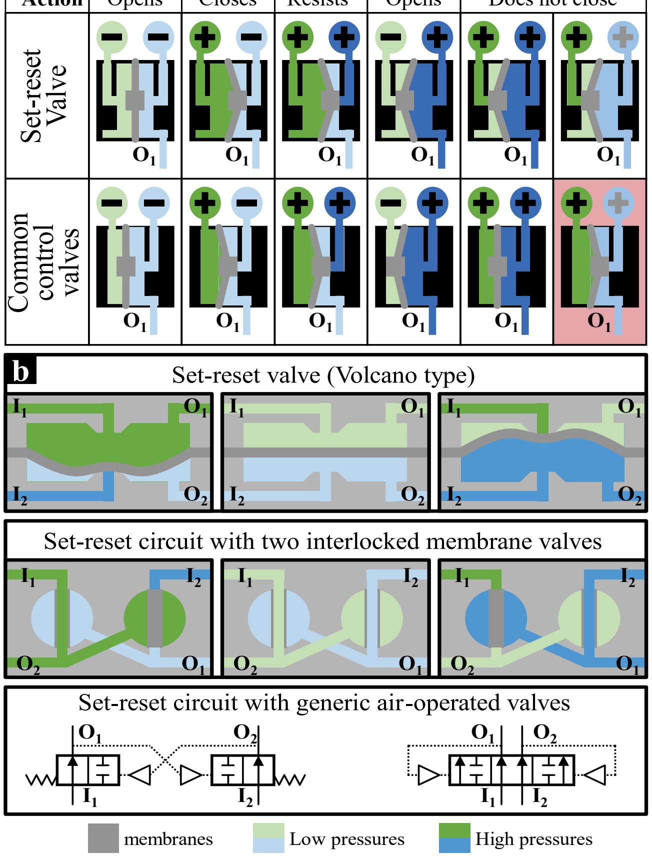

Fig. 2. Alternative types of valves. **(a)** Set-reset valves and common control valves used as selection valves. **(b)** Set-reset NAND latch achieved by set-reset valves, interlocked membrane valves or generic pneumatic valves.

IV. Improved Activation Processes

A key limitation in our initial prototypes was that the activation process was directly triggered by the final pulse of the selection process, which left no opportunity to adjust the pressures in the input lines to the desired values for each selected actuator prior to the activation. In the videos from the previous paper, the actuators (emulated by syringes) can be seen moving immediately upon activation, responding to the unmodified pressures present in their input lines.

For binary pressure systems, adding an extra selection valve before each activation valve allows the modification of the input line pressures before activation, except for the line used by the extra valve, which requires a low pressure pulse to trigger the activation. Fig. 3a shows both direct and indirect selection modules using this partial solution. In the emulated pressure plot, the selection ends with a low pulse on A, after which pressures in A, C, and D can be adjusted to any level of pressure. A red circle on the plot highlights the unavoidable low-pressure pulse on B required to trigger activation.

For multi-pressure systems, using activation valves that opens with activation pressure, higher than enable pressure, fully resolves this issue. Additionally, if the activation valves close (deactivate) with a pressure reduction back to enable pressure, check valves are not necessary to reset the system. Fig. 3b illustrates this solution, with the pressure in the enable line returning to enable pressure to deactivate the activation valves before reset.

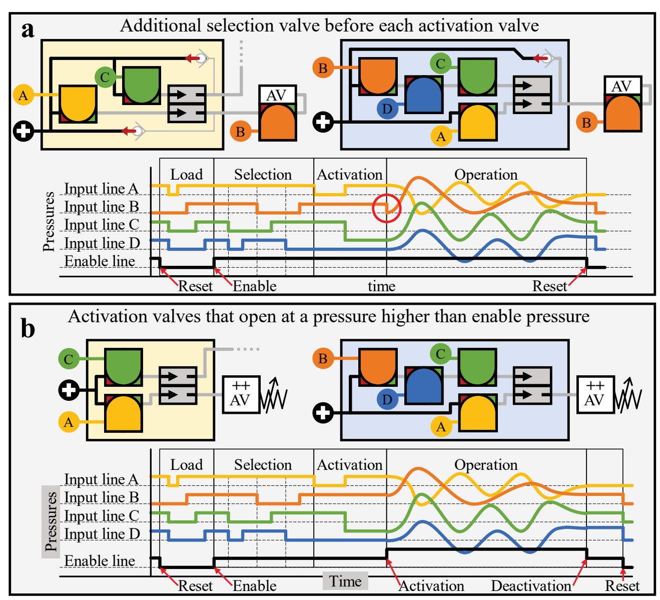

Fig. 3 Simulated examples of improved activation processes. **(a)** Limited improvement using an additional selection valve before each activation valve. **(b)** Improved activation process with activation valves that open at pressures over enable pressure and close again with enable pressure.

V. LONG LINEAR HIERARCHICAL NETWORKS

Direct selection systems like the prototype presented in the previous paper can provide compact and lightweight solutions for long inflatable robot arms or everting robots. However, each additional activation valve requires an extra pulse in the selection sequence. A simple way to shorten these sequences is to create barriers along the line and apply pulses to two or more input lines simultaneously, triggering a single-step progression up to the next barrier. Barriers can take the form of a change in the arrangement of the input lines, a single selection valve, a combination of both or more advanced mechanisms, such as a relief valve that opens with an overpressure pulse.

Fig. 4 shows two linear direct selection systems designed to maximize the number of modules with selection sequences within four pulses. The system on the left, with three input lines, integrates additional selection valves, labeled "<I>" as barriers: A pulse (BC) progresses directly to the first barrier, while pulses (BC, AB) reach the second barrier. The system on the right, with four input lines, combines additional selection valves and changes in the arrangement of the input lines: A pulse (BC) reaches module #5, that is connected to A and D, while a pulse (BCD) reaches directly the first single valve labeled "<A>".

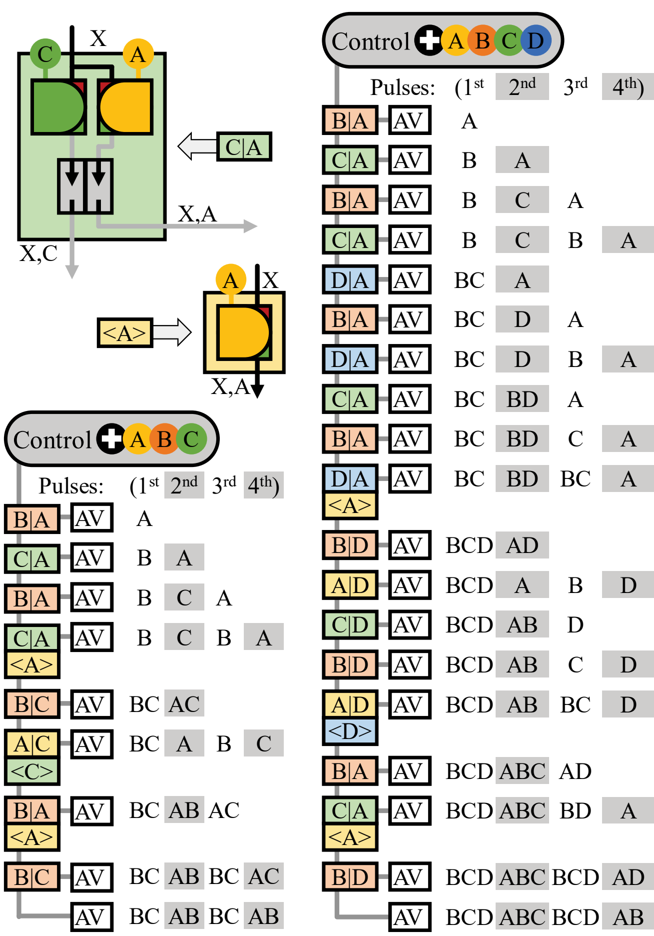

Fig. 4 Long linear hierarchical networks using three and four input lines and with selection sequences limited to four pulses. Modules labeled "I | J" correspond to direct selection modules and modules labeled "<I>" represent individual selection valves. Modules are colored according to the input line directing to the next module.

VI. STRUCTURED SELECTION SEQUENCES

A variation of the direct selection modules presented in the previous paper can be used to create complex modules for a non-hierarchical network, where each module can be selected with various structured sequences. For instance, in a hypothetical moon base pneumatic network, sequences could be structured as (doors > farm (all) > operate) or (instruments > sensors > #34). This method requires more valves but provides greater flexibility in the selection process, allowing bulk selection by type, tags, actions, or any other criteria.

Each basic module has a single output that opens with the correct sequence and get blocked with any other sequence until the system is reset. To create structured sequences, multiple basic modules are assembled in parallel and serial configurations, producing a variety of opening possibilities.

Fig. 5a shows all the modules for sequences with one or two pulses. As each module must ignore the last pulse used to open the previous module, the modules are labeled with their opening sequence and a prefix indicating which pulses are ignored before the first pulse. For example, module "C-A,B" opens with the sequence (A,B) ignoring pulses on C before A, so it can be used after a module that ends with C. The letters can be interchanged (e.g., "B-A,B" is identical to "D-B,D").

The grey selection valves connected to "I~Z" represent a parallel arrangement of selection valves connected to the existing input lines in that range.

Fig. 5b shows an application example using structured

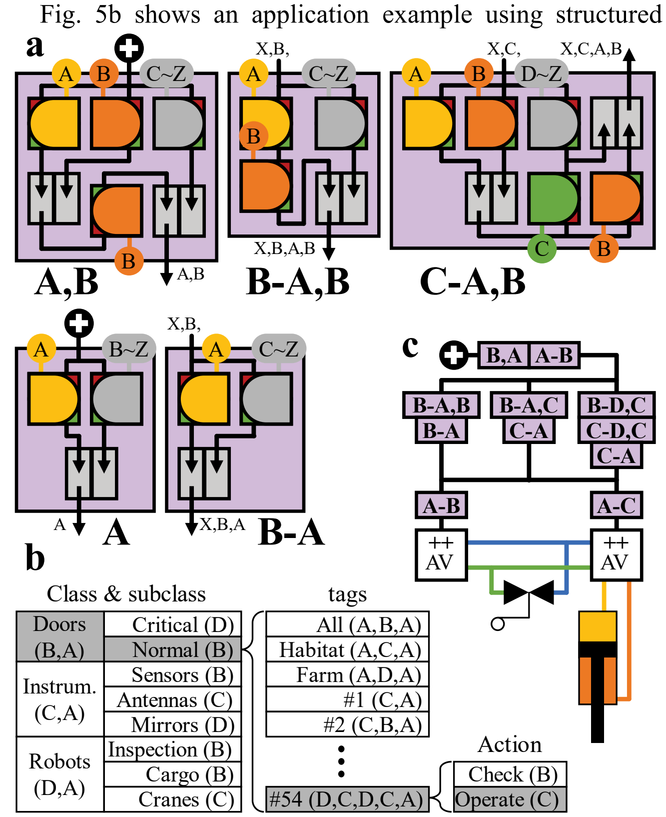

Fig. 5 Structured selection sequences. **(a)** Basic modules for sequences of one or two pulses. The grey selection valves connected to "I~Z" represent parallel arrangements of selection valves connected to each existing input line within that range. **(b)** Example of an application with structured sequences. **(c)** Diagram of the combination of basic modules corresponding to the door #54 of the application example. The icon connected to green and blue lines represents a contact sensor, while the icon connected to yellow and orange lines represents a bidirectional pneumatic cylinder.

sequences, where "Doors/Normal" can be selected “All” simultaneously with the pulses (A,B,A), by area with (A,C,A) or (A,D,A), or individually. For the chosen group, two possible actions are selectable. In this example, the total selection sequence would be the concatenation of the class, tag, and action. Fig. 5c shows the combination of basic modules necessary for the door #54 of the previous example: the beginning of the sequence, at the top, reads (B,A,B), corresponding to a "normal door." Afterwards, three parallel paths open corresponding to the location tags "all," "habitat," and "#54," and at the bottom, after receiving the sequence for any of those tags, two additional basic modules redirect to different activation valves, corresponding to the predefined actions. In the example, both activation valves connect a contact sensor to input lines C and D (green and blue), but only one connects also the input lines A and B (yellow and orange) to a pneumatic cylinder to actuate the door.

VII. Demonstration

Figure 6a shows a prototype used to validate the improved activation process described in Section IV. The prototype comprises two sections of a backbone robot arm, with each section actuated by three expansion cylinders (syringes) connected to an activation valve similar to those used in earlier prototypes, but incorporating an integrated spring (Fig. 6b). To operate a given section, the corresponding activation valve is selected using a direct selection fork, as in the circuit labeled "C|A" in Fig. 4.

The integrated spring keeps the activation valve closed at pressures below 60 kPa and requires pressures above 90 kPa to open. This design improves the activation process as explained at Section IV and also eliminates the need for vacuum to close the activations valves, although in this experiment we still use vacuum to contract the actuators.

The system was tested using -60kPa as low and reset pressures, 50kPa as enable and high pressure and 100kPa as activation pressure.

The operating cycle started with the load of the system (i.e. high pressure in all the input lines to close all the selection valves). As second step, enable pressure was applied to the enable line. Then, a single pulse in A or B was used as selection sequence to choose the section of the robot to be operated. Once the selection was performed, the pressures on each input line were changed to the last pressures applied to each actuator of the selected section and then the pressure in the enable line was raised to activation pressure to open the activation valve. After the operation of the selected section of the robot, the pressure in the enable line was reduced back to enable pressure to close the activation valve. The system was then reset by reducing the pressure in all the lines to -60kPa and a new operation cycle was started.

The robot was repeatedly tested with consecutive operating cycles and worked as expected. A video of the experiment is provided as supplementary material to this work. The adjustment of the pressures in the input lines to the desired levels for the actuators before the opening of the activation valves resulted in a smooth connection, without undesired movements of the robot due to pressure spikes.

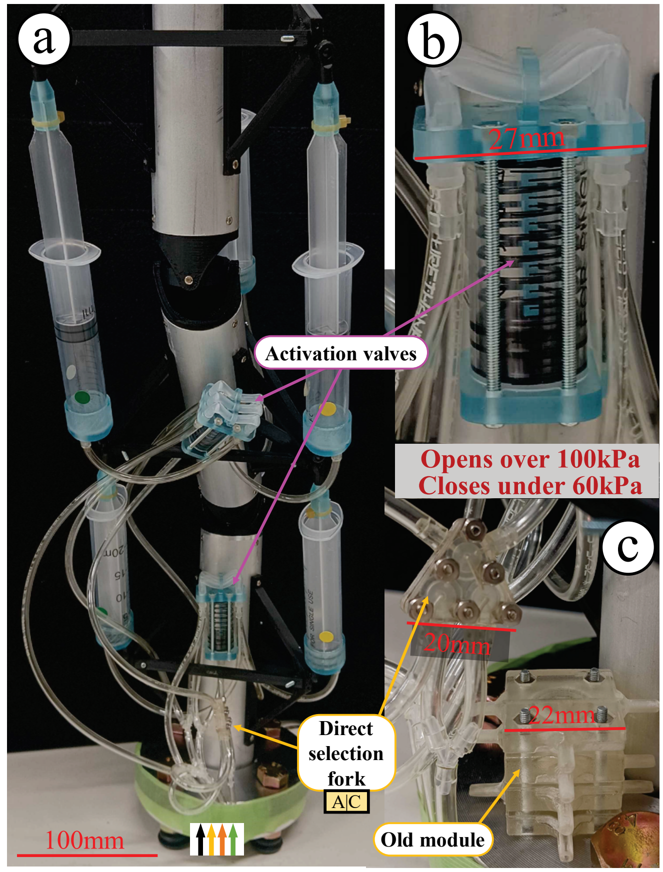

Fig. 6 Prototype with ++Activation valves. **(a)** Overview of a backbone robot arm, with two sections, each one actuated by three expansion cylinders connected to an activation valve. A direct selection module is used to select the section to be operated. **(b)** Close view of an activation valve with an integrated spring closing the valve. **(c)** Close view of the direct selection module used in this prototype compared to an older version (disconnected).

VIII. Conclusions and Future Work

The designs briefly outlined in Sections V and VI have not been validated through physical prototypes. Although these designs are based on simple selection valves and direct selection forks that were tested and validated in our previous paper, creating full prototypes of those systems would require considerable manufacturing effort, which would need to be carried out by a single researcher. These designs were set aside in favor of others with greater academic value that are currently under development.

In contrast, the improvement to the activation process discussed in Section IV was experimentally validated in Section VII. This aspect was prioritized because pressure spikes in the actuators during system activation can be a critical limitation for many applications that require smoother actuator response. The solution developed to address this issue has been incorporated into our current ongoing designs.

The logic systems introduced in the previous paper, along with the complementary designs and improvements presented in this brief work, demonstrate the versatility of the pneumatic multi-pulse selection systems for operating tethered or distributed pneumatic systems. However, the time required for the selection processes makes these systems impractical for applications that demand very fast actuator responses.

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