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Variable Logic Gate Mechanism with an AND ⇄ OR Meta-Switch and its Application for Grippers

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***Abstract*— Embodying intelligence in soft robots requires the design of logic circuits that do not rely on electrical components. Previous research has shown that it is possible to achieve logic gates that rely solely on rigid or even soft mechanical parts. Here, we present a purely mechanical system that can reversibly switch between two mechanical configurations of the logic gates AND and OR upon triggering by a meta-input. In addition, we present the first gripper with such a variable logic gate. Since the whole mechanism is mechanical, including the meta-input, this is a new breakthrough for robotics applications in environments where electrical circuits are unsuitable.**

I. Introduction

A. Embodied Intelligence in Robotics

Embodied intelligence in robotics refers to the ability of a robot to demonstrate intelligent behavior without relying on complex algorithms or centralized control systems, and plays a pivotal role in advancing the field of robotics[1]. The ability to respond to environmental cues is essential for all embodied intelligence. Soft robots, with their flexible and compliant structures, are particularly well-suited for embodying intelligence. From the viewpoint of information theory, an input (stimulus) is processed (computation) to generate an output (response). In particular, the computation itself may be "embodied" or encoded within the robot's physical properties and materials.

B. Mechanical Logic Gates

Logic gates (AND, OR, NOT, NAND, NOR, XOR, and XNOR) form the basics robotic computing, and are present in the microcontrollers and processors of robots in the traditional sense, in the form of electronic circuits. To this day, there have been numerous attempts to construct these logic gates using only mechanical parts[10]. In addition, promising efforts were made by the Whitesides group create a NAND gate without any rigid component. Their fluid dynamics approach is highly suitable for applications in robotics[11-15].

C. Scope of this Study

Here, we present the basic principle of a mechanical switch that changes the computation of a logic gate. As an example, we present the real prototype model for reversible switching between AND and OR logic gates, and illustrate this with the realization of a gripper with a variable logic gate that can reversibly switch between AND to OR modes in response to a meta-input. To the best of our knowledge, this is the first example of variable logic gate mechanism that is purely mechanical and doesn't rely on any electrical circuit. We expect these unconventional mechanical circuits to be critical for deployment in environments where electrical circuits cannot be used, such as underwater, inside a magnetic resonance imaging (MRI) machine, filled with flammable gas, or for the exploration of highly radioactive sites and so on.

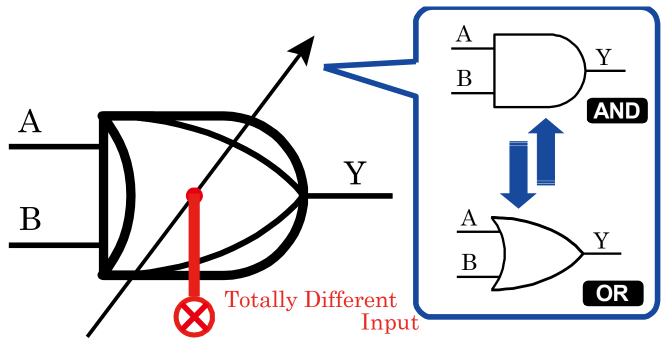

Figure 1. *Principle of the AND ⇄ OR reversible mechanism*

II. Concept of the Variable Logical Gate

A. Principle of the AND and OR Mechanical Logic Gates

The basic concept of the proposed variable logic gate mechanism is shown in Figure 1. Both the AND and OR logic gates consist of two inputs and one output. Here, we consider the possibility that a completely different input (meta-input) may be added on top of the two inputs, which significantly changes the function and basic characteristics of the device. This additional input may be of a completely different type than the first two, and must induce a change in the conformation of the system itself.

To illustrate this, Figures 2 and 3 show examples of AND and OR gates, respectively, consisting of a system of bellows, which is a type of elastic actuator. Importantly, this mechanical actuator may adopt not only the two states "0" or "1", as presented here, but also all of the intermediary states in between 0 and 1, which will allow going beyond the bimodal configuration.

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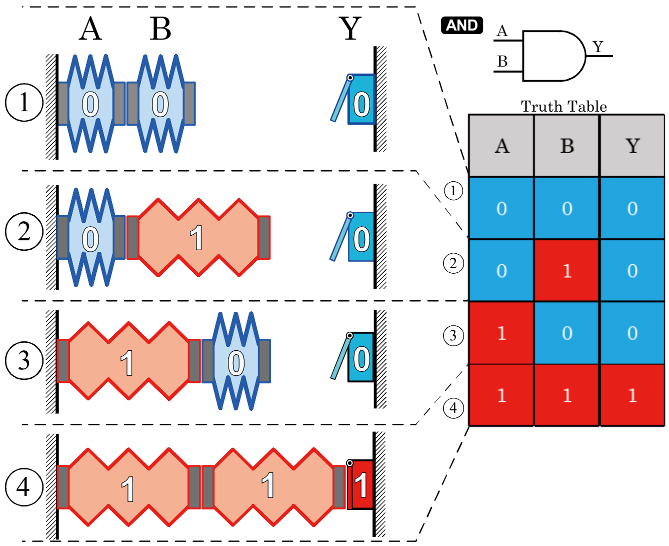


Figure 2. *Configuration of the AND logic gate*

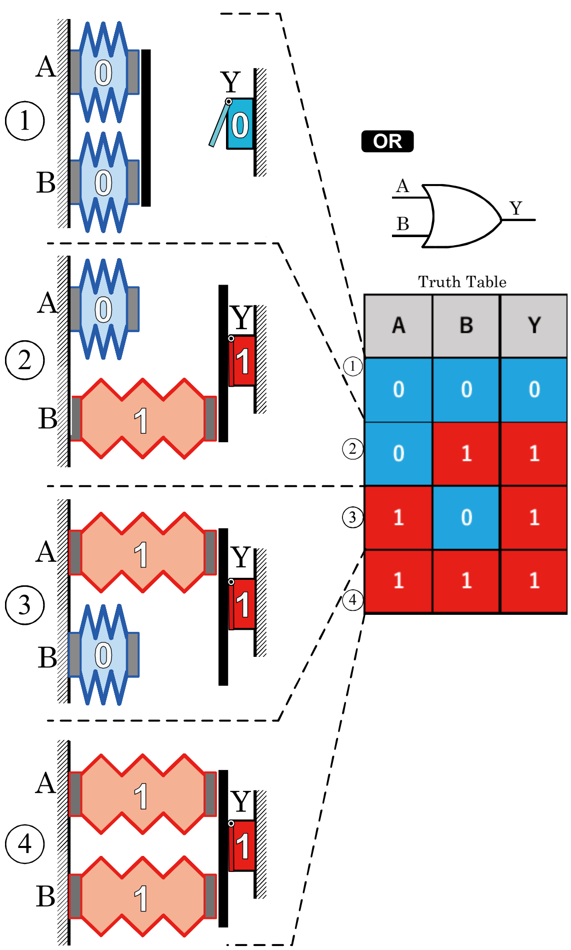


Figure 3. *Configuration of the OR logic gate*

B. *Principle of the Variable Mechanical Logic Gate*

When comparing the truth tables for AND (Figure 2) and OR (Figure 3), the only difference between these two logic gates are the expected outputs for when A≠B, which are "0" and "1" for AND and OR, respectively. In other words, the sole difference is where the threshold is set. This logically implies that in a mechanical configuration, it should possible to change an AND logic gate into an OR logic gate, and vice versa, by changing the physical position of a switch based on a different input system, thereby achieving the variable logic gate presented in this study.

Importantly, the input for changing the position of the switch should be completely separate from the inputs for the logic gate (A and B). Specific examples of separate input systems may include pressure differences (underwater *vs* air), temperature changes or gradients, gravitational or magnetic fields, or a change in gravitational direction, among others.

C. *Configuration of the Variable Logic Gate*

The basic configuration of the variable logic mechanism is shown in Figure 4. As an example, in this study, we opted for a straight-line serial configuration.

Importantly, the direction of the switch is perpendicular to the direction of the actuator's extension. This is different to the configuration presented in Figures 2 and 3, where the switch is directly facing the actuator. This is because the latter case would require an additional free joint and equalizer, increasing the complexity of the system. In the interest of simplicity, the switch (Y) is set to be perpendicular to the extending actuator (Figure 4).

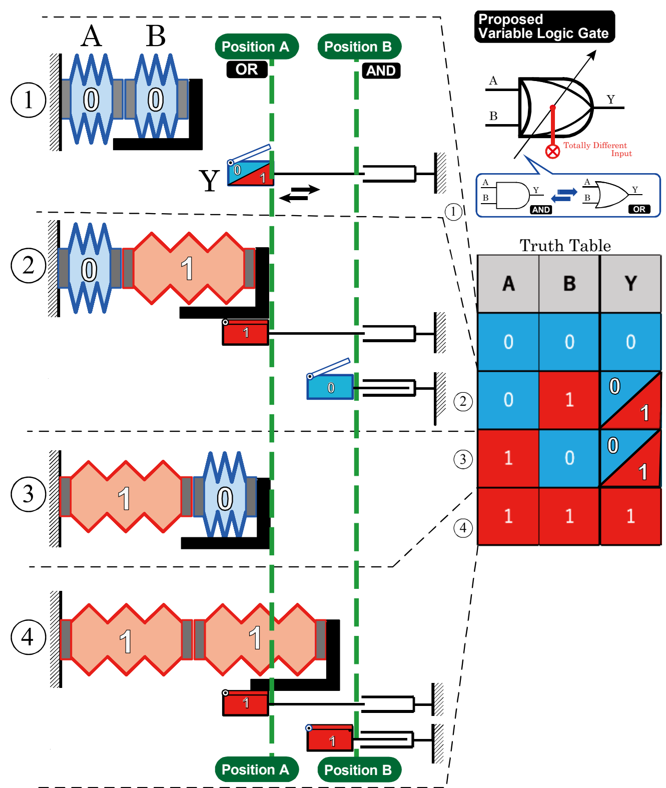


Figure 4. *Configuration of the proposed variable logic gate (straight-line serial type)*

D. *Applications of the Variable Logic Gate Mechanism*

This section discusses example applications of the variable logic gate mechanism described above. First, let us consider the case of a forward-moving vehicle with two input channels on its left and right side. In the OR mode, the vehicle stops when either one or both of the left and right sides make contact with an object (Figure 6, left). In contrast, in the AND mode, the vehicle keeps moving forward even after one of the sides first makes contact with the object. This contact point creates resistance, causing the vehicle to turn until the other side also contacts to the object, meaning that the vehicle will eventually stick closely or wrap itself around the object (Figure 6, right).

Similarly, a gripper with a flexible tip may stop when one of the inputs is activated in the OR mode, whereas in the AND mode, the flexible part would deform until all inputs are in contact with the target (Figure 6). As illustrated by the two examples above, the mechanical variable logic gate enables two distinct operating modes with different characteristics. In addition, the switching between OR and AND modes may be achieved in a variety of ways, including changing the orientation of the robotic mechanism, or changing the environment from air to water, or vice versa.

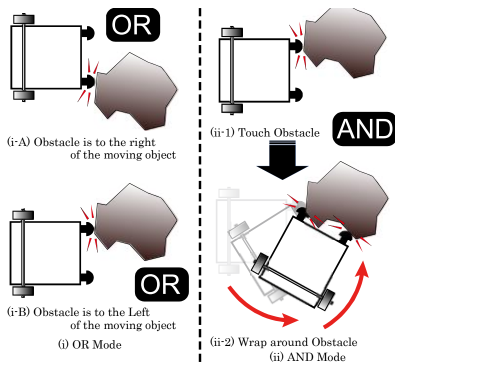


Figure 5. *Application of variable logic gate to a moving vehicle*

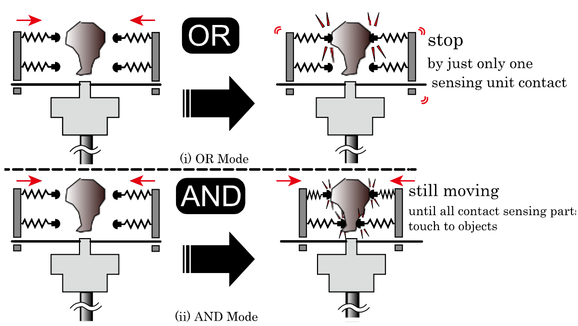


Figure 6. *Application of variable logic gate to a gripper mechanism*

III. Design and Fabrication

A. Setting the Prototype Configuration

To simplify the proof of concept prototype for the variable logic gate mechanism described in Section II, an artificial muscle actuator was used instead of an extensible (bellows) actuator, as the latter is prone to buckling. Figure 7 shows the configuration of the device built in this study. In the OR mode, when A or B are pressed, the artificial muscles A or B contract depending on the input. As a result of this, if the Y switch is turned on, air will be released.

In the OR mode, if neither A nor B is pressed, neither A nor B changes, and switch Y is not pushed; however, if both A and B are pressed, both muscles contract, resulting in twice the displacement. Thanks to the L-shaped part on the right side of Figure 7, switch Y is pressed even in this double displacement position, and the final output is made.

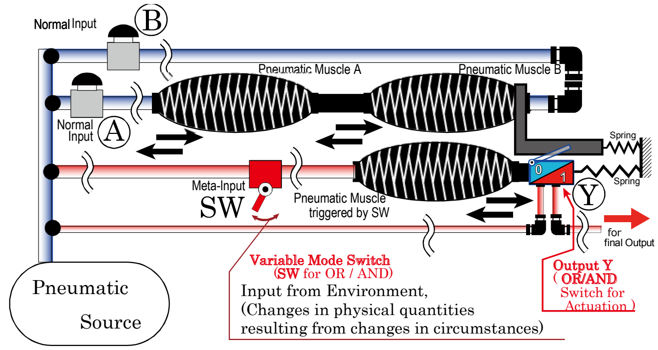


Figure 7. *Application of variable logic gate to a gripper mechanism*

On the other hand, in the AND mode, when either A or B are pressed, artificial muscles A or B contract accordingly. However, due to a separate input system, the artificial muscle in the lower part of Figure 7 has contracted and moved to the left. Therefore, even if one of the artificial muscles, A or B, contracts, switch Y cannot be reached. Of course, if neither A nor B are pressed, neither artificial muscle will contract, and of course, switch Y will not be activated. Finally, if both A and B are pressed, it contracts twice as much, reaching a position where it can press switch Y, resulting in the final output.

B. Prototyping

Figure 8 shows a diagram of the external appearance of the prototype, and Figures 9 and 10 show its main top view. The size and specifications are as follows.

Pneumuscle PMJ40×30-UK-Q by Koganei was used for the artificial muscles, and PMJ40×40-UK-Q was used as a linear actuator that changes the position of switch Y. The initial lengths of these actuators are approximately 30 mm, 40 mm, and 40 mm, respectively. The extension and contraction strokes are about 8 mm and 14 mm at 0.4 MPa pressure, respectively. The spring constant on the right end of the upper row in Figure 7, which corresponds to the input side of A and B, is 0.0164 [N/mm], and the spring constant of the spring on the right side of the switch used as the variable trigger in the lower row is 0.0472 [N/mm]. This is necessary to prevent the artificial muscle on the right side of the switch from buckling under the influence of the artificial muscle on the upper level, which is normally activated by inputs A and B, when switch Y is not turned on. This means that a spring constant that generates tension on the right side of switch Y with a force greater than the minimum push force required to activate switch Y must be set to achieve the desired switching function. The following movie shows the switching operation for this spring constant. In the movie, the buckling of the artificial muscle is prioritized over switching until around the 10-second mark, but at the 12-second mark, the tension of the spring is increased and the switching function is activated (Video: https://youtu.be/m65qZz_7h5E). The switch operability as a function of spring tension is shown in Figure 11.

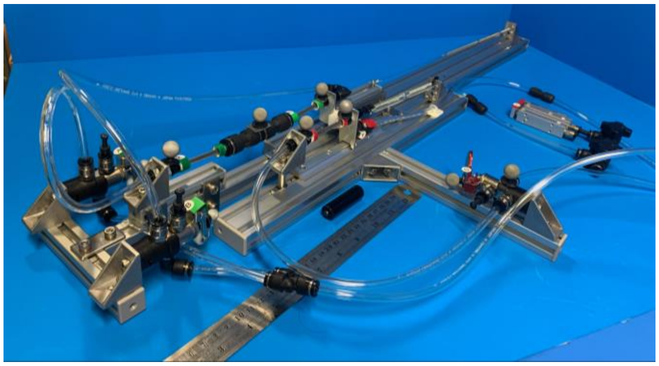


Figure 8. *External appearance of the prototype (global view)*

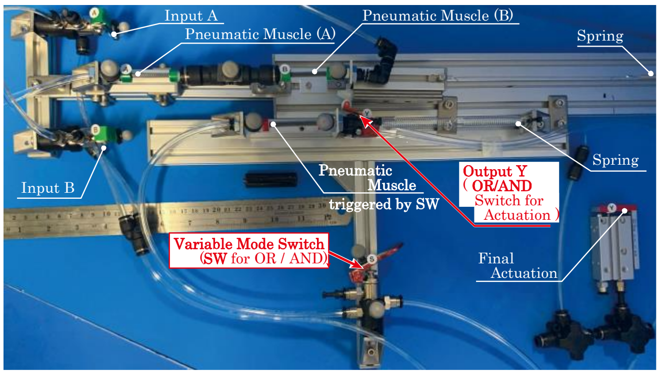


Figure 9. *External appearance of the prototype (main component)*

Experimental Results

A. Basic Input-Output Relationship

Using the prototype machine shown in Figures 8-9, we conducted basic experiments to verify the functionality of the inputs and output. Practically, this was confirmed by pressing the two input contact sensing parts in OR and AND gate mode, as well as testing the ability to switch between AND and OR modes (Video: https://youtu.be/z0IFjYYrt4U). Representative moments of each input-output action were captured from the video and displayed in Figures 10-16. The prototype behaved as expected.

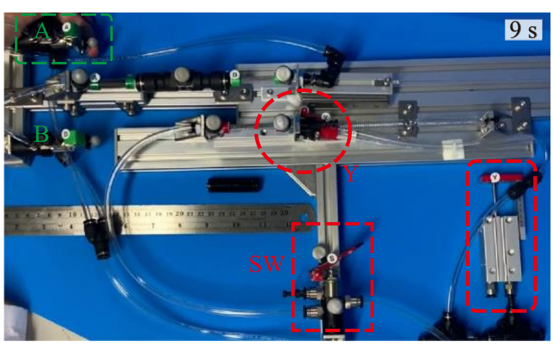


Figure 10. *OR mode with activated input A (upper left): the central switch (SW) Y is pressed, causing the cylinder at the bottom right to extend*

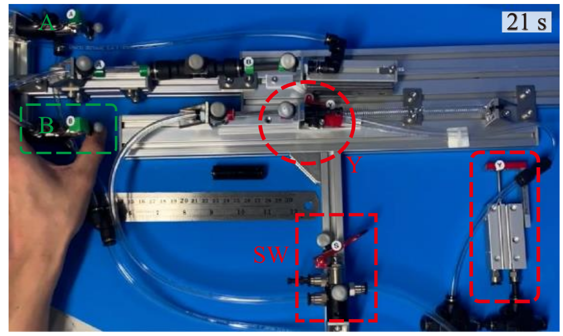


Figure 11. *OR mode with activated input B (upper left): the central switch (SW) Y is pressed, causing the cylinder at the bottom right to extend*

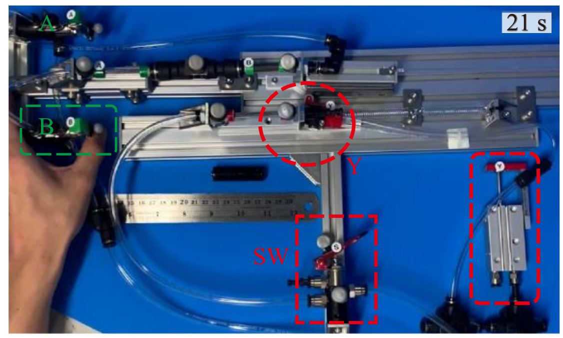


Figure 12. *OR mode with activated inputs A and B (upper left): the central switch (SW) Y is pressed, causing the cylinder at the bottom right to extend*

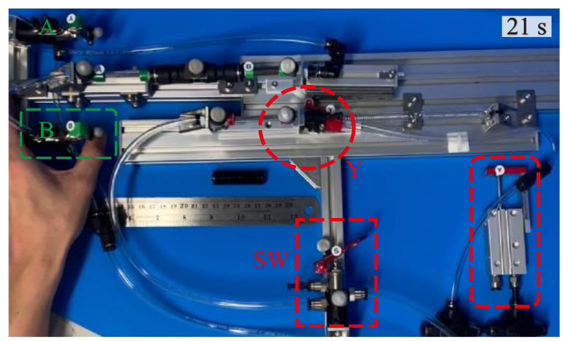


Figure 13. *Switching from OR to AND mode: the separate trigger at the bottom center is pressed, causing the artificial muscle in the lower lane to contract, and the position of the central switch Y (SW) shifts to the left*

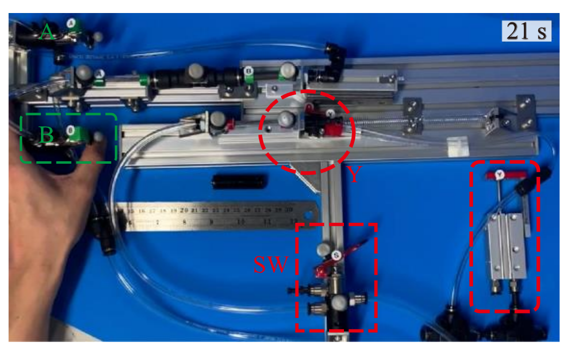


Figure 14. *AND mode with activated input A (upper left): the central switch (SW) Y is pressed, and the cylinder at the bottom right does not extend*

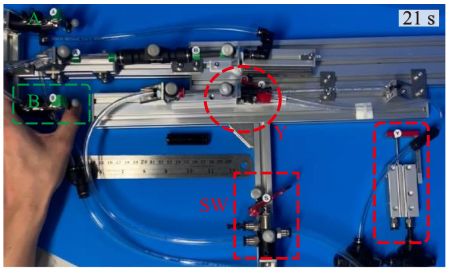


Figure 15. *AND mode with activated input B (upper left): the central switch (SW) Y is pressed, and the cylinder at the bottom right does not extend*

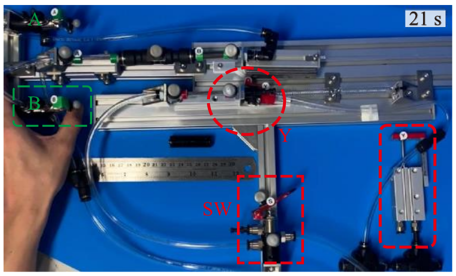


Figure 16. *AND mode activated inputs A and B (upper left): the central switch (SW) Y is pressed, causing the cylinder at the bottom right to extend*

B. *Motion Capture Analysis*

To quantitatively evaluate the prototype, we measured the linear displacement or stroke of each component as a function of time using motion capture, using the experimental setup described in Figure 17. The motion capture system used was the Optitrack Prime 13W from Natural Point Inc., USA. The measurements were conducted using three units (1.3Mpixel resolution, 120FPS frequency). The results are presented in Figure 20, where the horizontal axis represents time (in seconds) and the vertical axis shows the stroke of each marker. The dashed red box in Figure 18 indicates the timing when the system transitioned from OR mode to AND mode, showing input-output responses that are consistent with the truth table.

In OR mode, the cylindrical tube extends when either A or B is "1". In AND mode (after the red dashed line, when only A is "1" (around the 40-second mark), as well as when only B is "1" (around the 46-second mark), despite a slight oscillation in the vertical direction due to vibration, the OR/AND switch (Switch Y) does not engage, indicating that the perturbation was not enough to activate it, as expected (Figures 21-24).

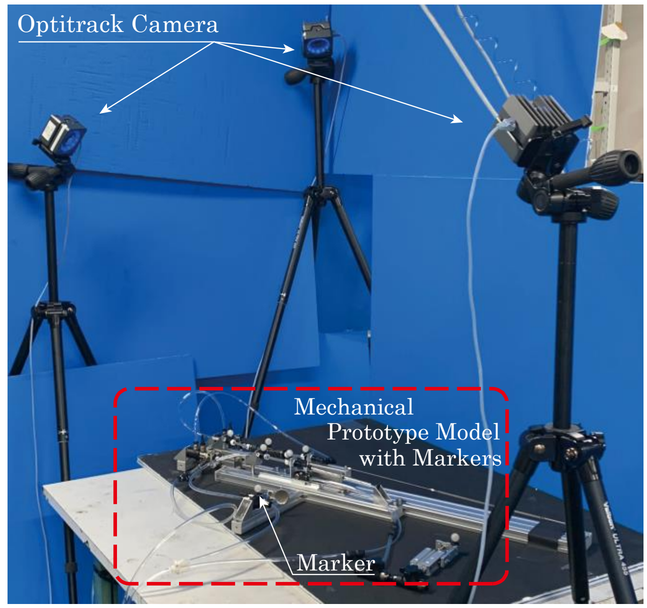


Figure 17. *Experimental setup for the motion capture*

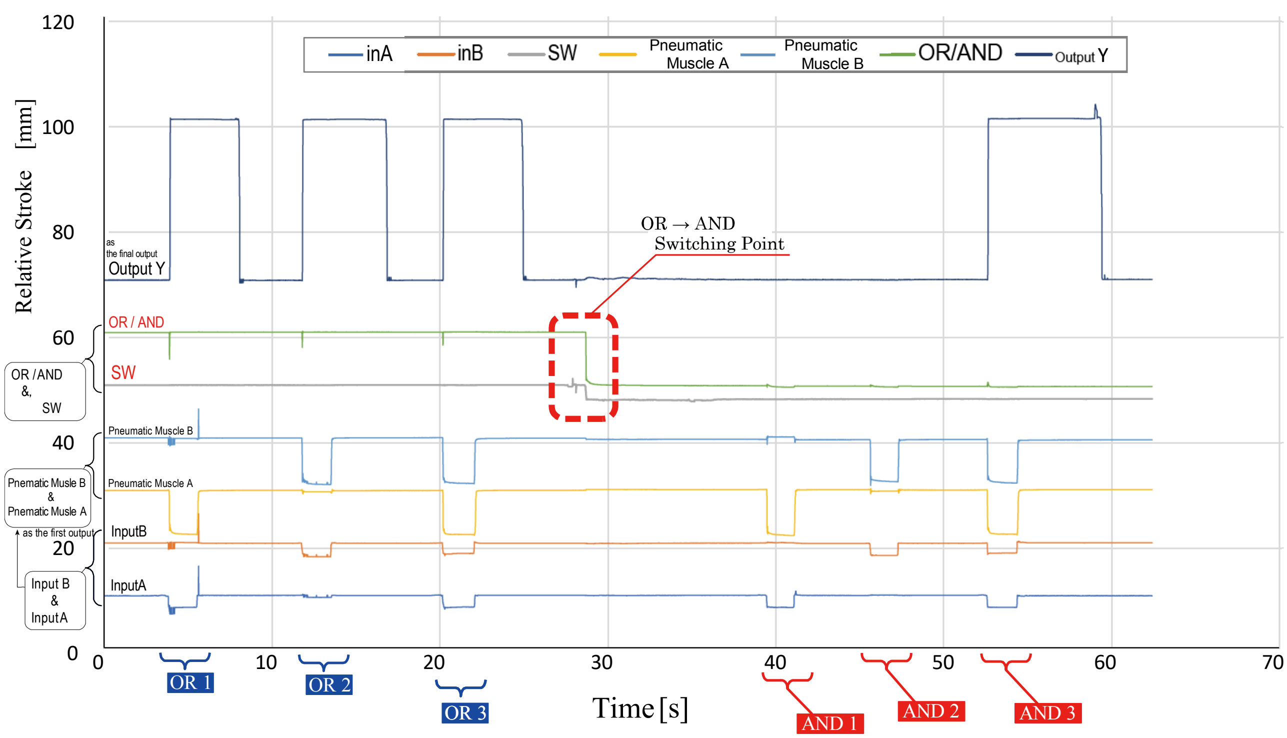


Figure 18. *Results for the motion capture analysis of variable logical gate mechanical prototype (X-axis: time elapsed, Y-axis: stroke)*

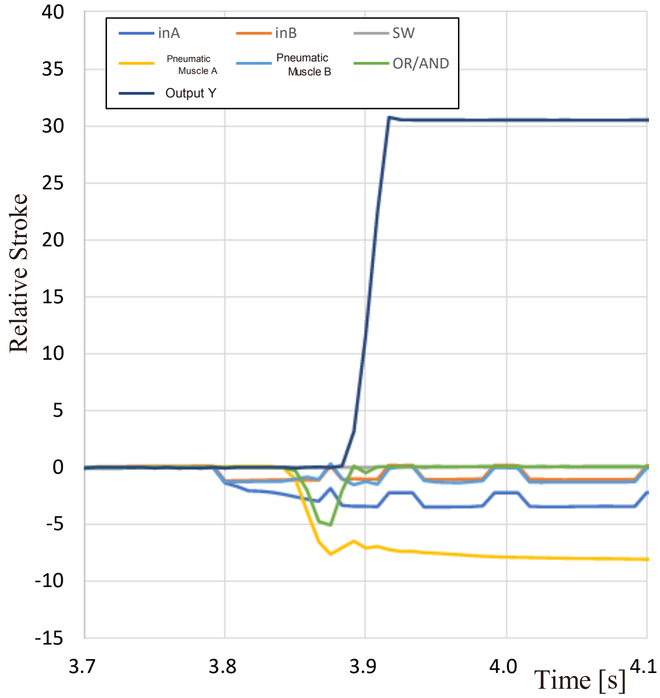


Figure 19. *Transient response in OR mode (with input A=1, B=0. Enlarged section from 3.7[s]-4.3[s] around "OR 1" in Figure 20)*

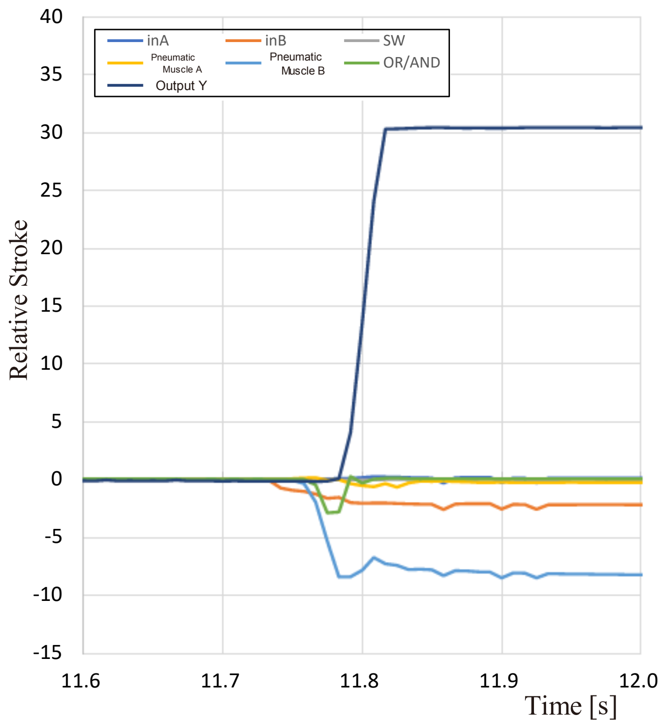


Figure 20. *Transient response in OR mode (with input A=1, B=0. Enlarged section from 11.6[s]-12.0[s] around "OR 2" in Figure 20)*

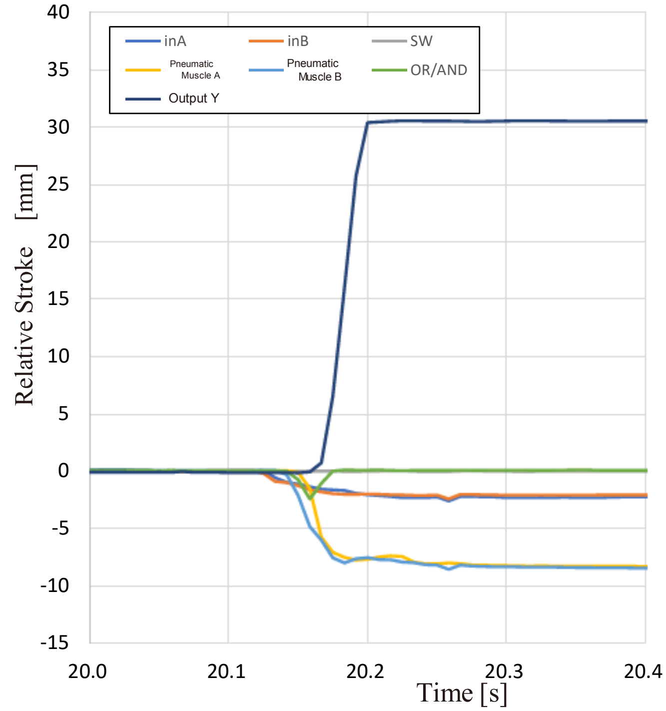


Figure 21. *Transient response in OR mode (with input A=1, B=1. Enlarged section from 20.0[s]-20.4[s] around "OR 3" in Figure 20)*

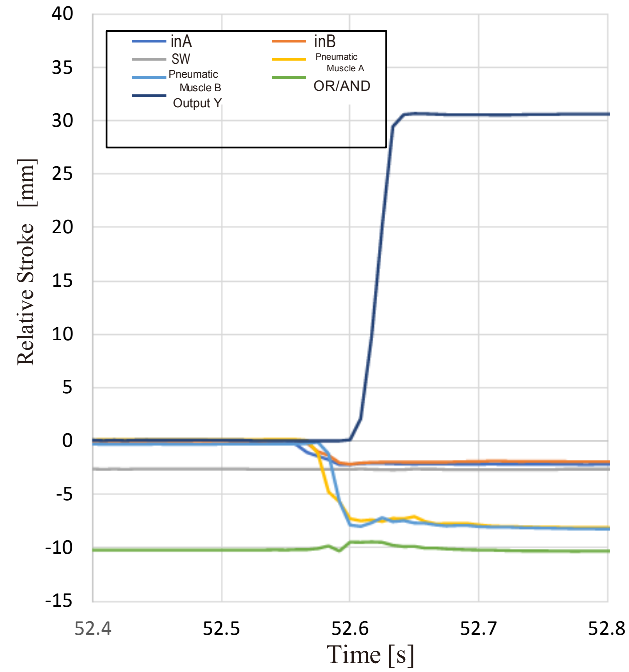


Figure 22. *Transient response in AND mode (with input A=1, B=1. Enlarged section from 52.4[s]-52.8[s] around "AND 3" in Figure 20)*

C. Transient Response Time at each Rising Edge

The transient response time at each rising edge is presented in Figures 19-22. As observed, the rise consistently settles within 0.1[s], suggesting that the performance of this initial prototype is satisfactory for practical use. On the other hand, we believe that by further harnessing the intermediate states between "0" and "1" as functional outputs, it is possible to go beyond simple information processing, by configuring it such that actuators like artificial muscles exert additional outputs as mechanical effects on the external environment. This will lead to the development of logic gate mechanisms that uniquely integrate both information processing and mechanical actions.

IV. Variable Logic Grippers

A. Gripper Configuration

In this study, as an example application of the mechanical variable logic gate, we developed a gripper equipped with two mechanical touch sensors at the fingertips (Figure 25). For meta-inputs that switch between AND and OR in the variable logic gate mechanism, one might consider using the gripper's orientation relative to the direction of gravity. The ability to change the properties of the system depending on whether the gripper approaches the target object diagonally (past a certain preset angle) or horizontally is crucial. An illustrative task that leverages this advantage is bulk picking (Figures 23 and 24). When picking, the OR mode is utilized to grasp just one item from a bulk stack, while, in contrast, when gripping a box from the horizontal direction, the AND mode is employed to seamlessly grasp the contour of the box, without concerns about the box's creases or other details.

To construct the prototype gripper, we employed an air pressure hand with a 100[mm] stroke: MHL2-25D1. On each of its left and right fingers, we incorporated a cylinder (MSPCN10-60 with a 60[mm] stroke) that variably adjusts the spring tension using internal pressure (intended solely for variable spring use, not for driving) as shown in Figures 6 and 25. Furthermore, an independent input was achieved using a lever with a weight at its tip, such that the machine's inclination serves as the input.

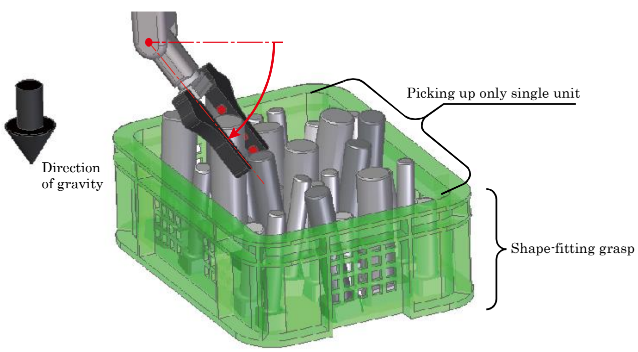


Figure 23. *Pickup of a single object from a diagonal approach using the variable logic gripper (OR mode)*

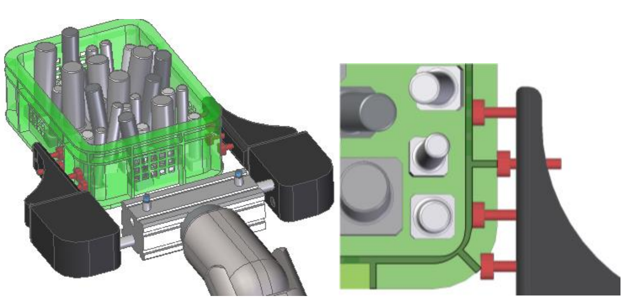


Figure 24. *Horizontal shape-conforming grasping of a box with an irregular edge using the variable logic gripper (AND mode)*

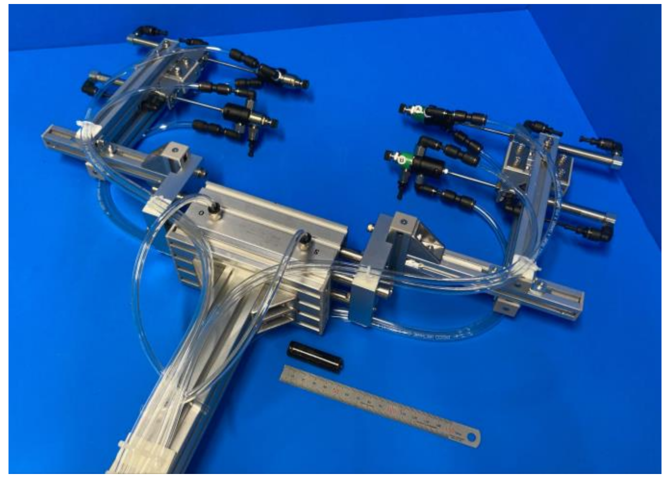


Figure 25. *Appearance of the variable logic gripper prototype*

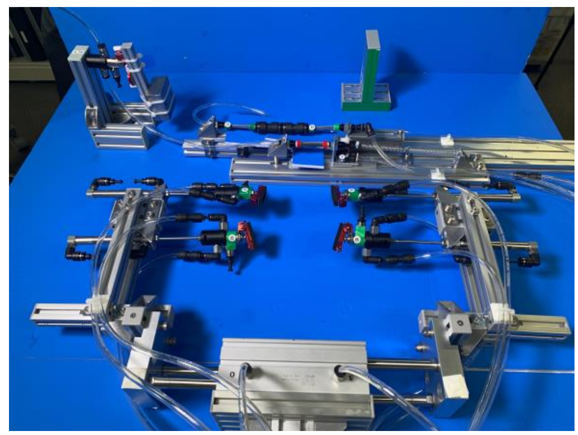


Figure 26. *Appearance of the variable logic grasping experiments*

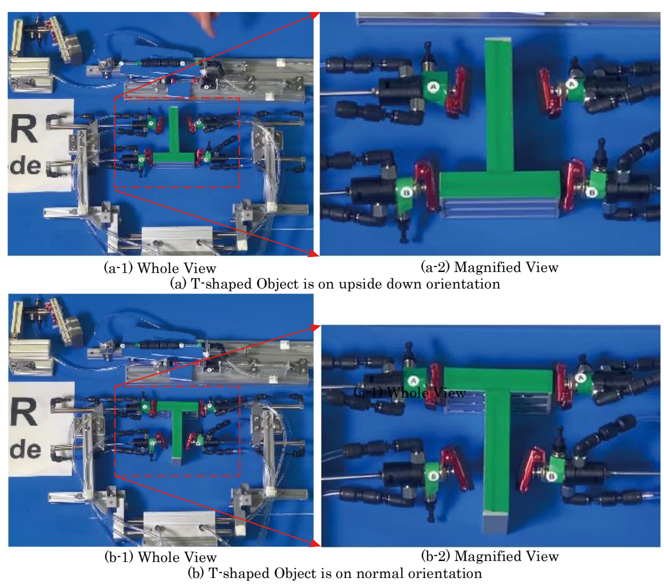
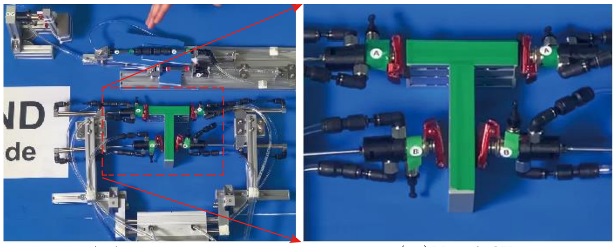
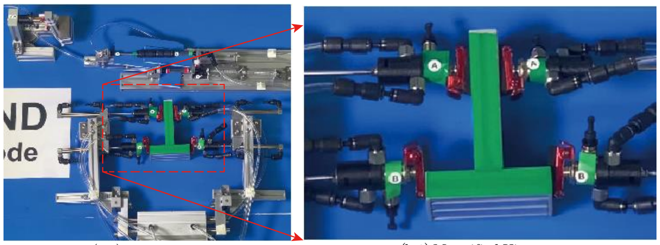


Figure 27. *Grasping on OR mode*
(Please watch the movie https://youtu.be/FwvKtOzXsMw)



(a-1) Whole View (a-2) Magnified View
(a) T-shaped Object is on normal orientation



(b-1) Whole View (b-2) Magnified View
(b) T-shaped Object is on upside down orientation

Figure 28. *Grasping on AND mode*
(Please watch the movie https://youtu.be/FwvKtOzXsMw)

B. Experimental Results using the Variable Logic Gripper

Using the gripper equipped with the variable logic gate function, a gripping experiment was conducted on a T-shaped object. In the experiment, the orientation of this T-shaped object was adjusted such that the horizontal bar of the "T" was oriented towards the base of the gripper's fingers. Another test was done with the T-shaped object rotated by 180 degrees so that the horizontal bar was oriented towards the fingertip side. The default for Output Y, as shown in Figure 9, was set as the gripper's "open" status, meaning that when Y is activated, the gripping starts gripping.

Figures 26-28 show the experiment's proceedings. In OR mode, as shown in Figures 27, the gripper halted its closing action when the horizontal bar of the T-shaped object touched either the base or the tip of the hand, out of a total of four contact points. In contrast, in AND mode, as shown in Figures 28, even if the horizontal bar of the T-shaped object first contacted the mechanical switch, the gripper continued its closing action until all four mechanical switches were pressed, achieving a conformal grip.

V. Conclusions and Future Work

In the past, mechanical logic gates which do not rely on any electric circuit have been proposed, but only consisted of one single logic gate. Here, we propose a purely mechanical variable logic gate mechanism useful for the operations in environments where electrical circuits cannot be used, such as underwater, inside a magnetic resonance imaging (MRI) machine, filled with flammable gas, or for the exploration of highly radioactive sites and so on. This mechanism features a physical change in the configuration of the entire system, wherein a meta-input leads to the switching between AND and OR logic gates. Based on this principle, a prototype was designed and tested. Challenges such as adjusting the spring constant to enable correct activation of the switch in response to the meta-input were also addressed. Using motion capture, the relative strokes of each part were quantitatively measured, confirming the basic effectiveness of the prototype based on the devised principle.

In the future, we plan not only to expand the concept to other logic gates beyond AND and OR, but also to explore variations in the type and number of meta-inputs, including the intermediary states between "0" and "1".

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