

Programmable Switching of Fluids via Pre-twisting

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Abstract—Manipulating airflow is important for controlling pneumatically actuated soft robots, however, current switching techniques suffer from leakage under high pressure (>200 kPa) or require a complex fabrication process. We propose a new method for reliably and repeatably cutting off airflow by harnessing pre-loaded torsional forces applied to our tubing. The switching distance and hysteresis of our pre-twisted tubing are programmable by varying the tube length and the twisting angle. Our experiments demonstrate the use of pre-twisted tubing to implement CMOS equivalent fluidic switches configured as NOT-, AND-, and OR-gates, and a distance sensor for feedback control for the oscillation of a PneuNet. Our approach of pre-loading tubes with a torsional force allows for simplicity, integrated functionality, and the capability of manipulating high-pressure, fluidic signals mainly at the cost of tubing.

I. INTRODUCTION

Soft robots are made from compliant materials; they are suitable for human interactions [1], can adapt to different environments [2], and their control is comparatively simple in contrast to conventional, rigid robots [3]. Among the actuation methods for soft robots, pneumatic actuation is particularly popular due to its low cost, simple fabrication, and the availability of components [4]. However, most pneumatic control systems consist of cumbersome electrical and electronic components (microcontrollers, power electronics, and valves), presenting comparatively sophisticated infrastructure for otherwise low-level control and autonomy [5, 6]. To reduce the cost and complexity of pneumatic control systems, there is an increasing research effort on designing electronics-free, fluidic control components.

Microfluidic techniques have been developed for decades and are capable of fluidic computation and switching [7], however, the low flow rates in the range of 0.1-10 mL/min are unsuitable for most pneumatic soft actuators [8, 9]. To achieve high flow rates (>1 L/min) for a given pressure, channel sizes need to be increased; numerous *macrofluidic* soft logic elements have been recently introduced and stacked to achieve circuit-level functionality. The soft bistable valve has been showcased as a CMOS-equivalent switch [10], digital soft logic [11], a soft ring oscillator [12], and non-volatile memory [13]. Robot motions, such as walking [14,

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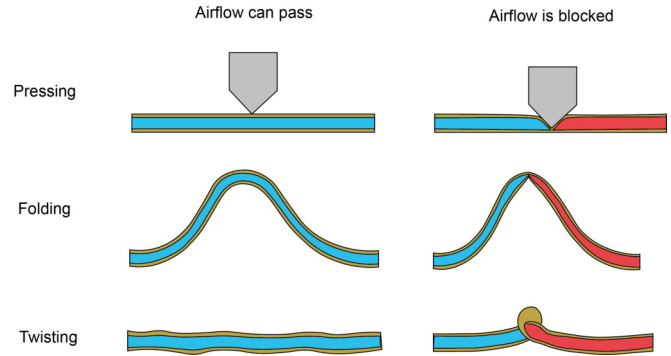


Fig. 1. **Qualitative analysis of tube kinking techniques for fluid flow regulation.** The figure illustrates three distinct methods for achieving tube closure to regulate fluid flow. The pressing method employs force at the contact position to seal the tube, necessitating increased force in proportion to airflow pressure. The folding method utilizes tube deformation to self-kink and close, requiring less force but occupying more spatial volume. The twisting method employs torsional force to form coils, thereby achieving a large inner surface contact area suitable for blocking high-pressure airflow.

[15], swimming [16, 17], climbing [16], and grasping [10] have all been demonstrated with soft elements as the fluidic control components [10, 18].

Three distinct methods for tube kinking facilitate fluid flow regulation: pressing, folding, and twisting (**Figure 1**). The permissibility of airflow is contingent upon the contact area of the tube's inner surface. Specifically, the absence of a gap between the inner surfaces results in the complete obstruction of airflow.

The pressing method employs crimping of the elastic wall of the tube to obstruct airflow. For complete closure of the cross-section of the tube and prevention of leakage, a rigid component often serves as the force applicator at a localized contact point. For instance, tube-balloon-logic achieves airflow cessation by inflating a balloon that exerts a force on a V-shaped bent straw positioned against the tube, with a maximum operational pressure of 200 kPa [19]. As the operational pressure increases, the requisite force for closure correspondingly increases.

Folding stands as the predominant tube kinking technique in the realm of soft valve designs. When configured in a curved arrangement, the tube can self-kink under minimal force, obviating the need for rigid components. Various implementations exemplify this approach: the bistable valve employs a soft dome-shaped membrane to induce tube folding [10], while the buckling sheet ring oscillator utilizes a buckling plastic sheet for the same purpose [16]. Luo et al. illustrate that altering the distance between two fixed ends of an elastic tube can also induce folding [20]. However, these

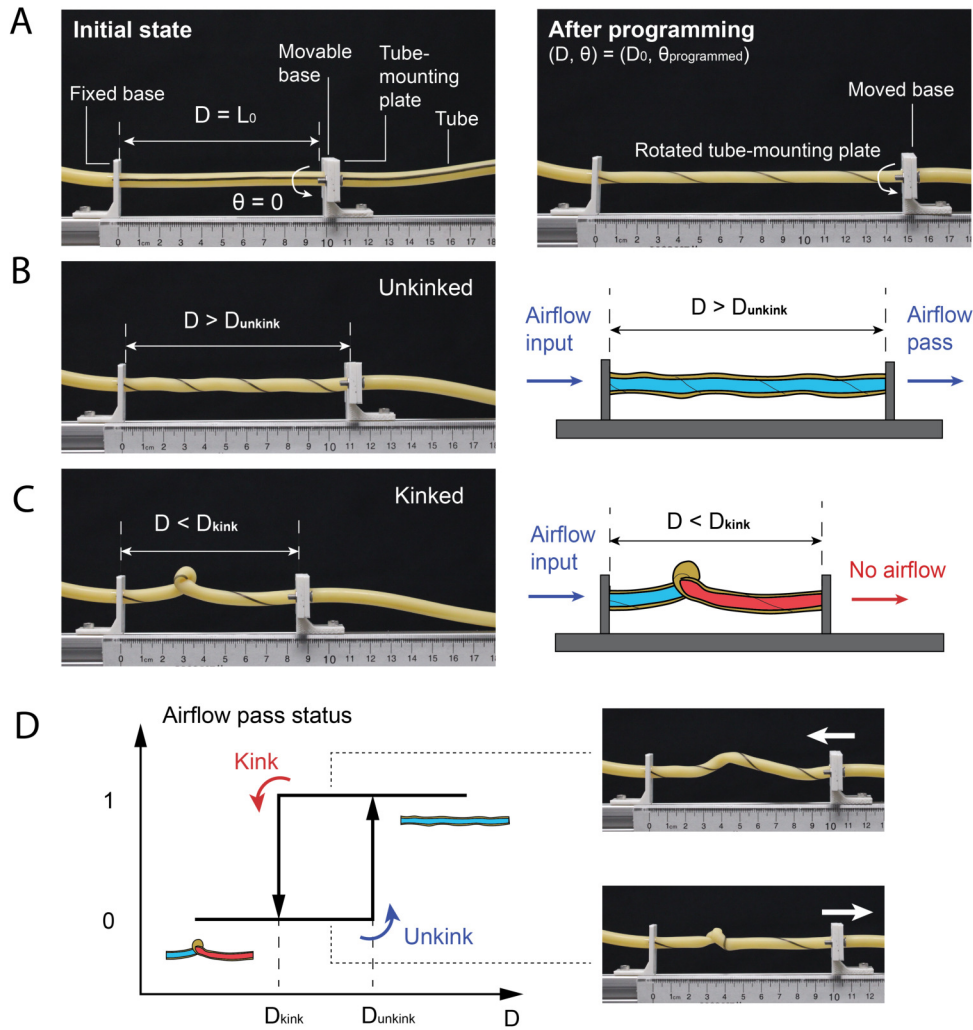


Fig. 2. **Operational principle of pre-twisted tube switch.** (A) Initial and post-programming states of the tube, where the tube remains unstretched and untwisted initially. (B) Experiment and schematic of the tube in its unkinked (off/closed) state, with the distance D exceeding the threshold unkink distance D_{unkink} . (C) Experiment and schematic of the tube in its kinked (on/open) state, where D is less than the critical kink distance D_{kink} . In this state, one or multiple kinks form to obstruct airflow. (D) Dynamic behavior of the tube as D varies: when D falls below D_{kink} , a kink forms to halt airflow, and when D surpasses D_{unkink} , the kink unravels to permit airflow. Experiments show intermediate states of hysteresis.

methods typically exhibit a maximum operational pressure of 80 *kPa*. Decker et al. enhance this performance by combining folding and pressing within a straw, thereby augmenting the inner surface contact area and elevating the maximum operational pressure to 165 *kPa* in their cost-effective programmable valve design [21].

The twisting method involves the application of torsional force to the tube. Upon reaching a sufficient level of torque, the tube undergoes buckling, leading to contact between the inner surfaces. Further increase in the twisting angle can result in the tube becoming kinked, thereby obstructing airflow. The advantage of this method lies in its ability to generate a large inner surface contact area, making it suitable for blocking high-pressure airflow. Wang et al. conducted an investigation into the torsional responses, both in terms of deformation and torque, of twisted elastic tubes. However, their study only briefly examined the ability of the tube to block airflow at a pressure of 100 *kPa* [22]. In their proposed

valve design, a twist exceeding 360 degrees is necessary to transition between the fully closed and fully open states, a range that surpasses the motion capabilities of most existing torsional pneumatic actuators [23].

In this paper, we present a robust method for programmable fluid-switching by altering the length of a tube that has been pre-twisted or ‘programmed’. The main contribution of this work includes:

- 1) A novel fluid-switching technique capable of regulating airflow under pressures reaching up to 280 *kPa*.
- 2) A comprehensive analysis of the programmability of our tube in relation to tube length and twisting angle.
- 3) Demonstrations of using the programmable switch as NOT-, AND-, and OR-gates, and distance feedback control for the oscillation of a PneuNet.

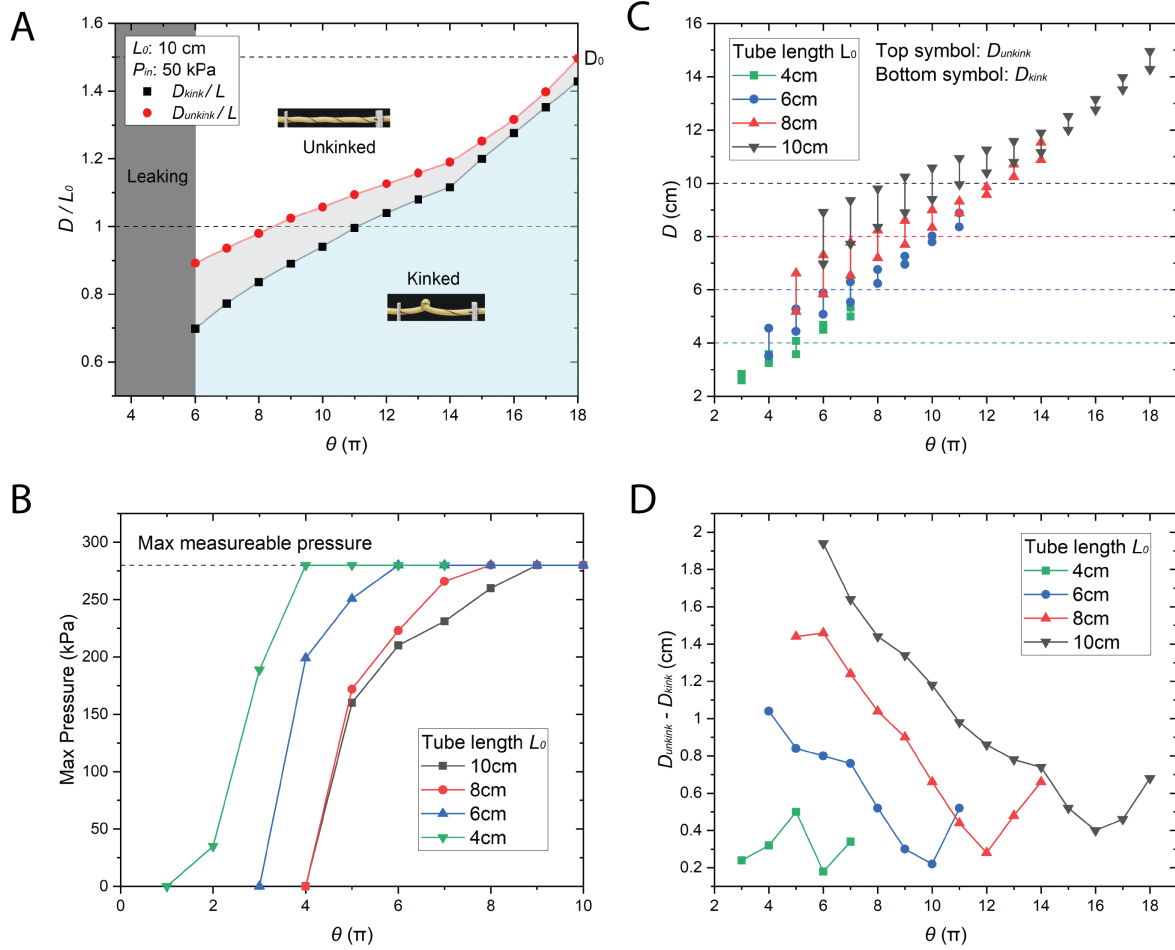


Fig. 3. **Characterization of pre-twisted-tube switch.** (A) D/L_0 as a function of the twisting angle θ . When θ is smaller than 6π (dark gray), no kink can be formed or the kink is insufficient to block the 50 kPa operating pressure. When the distance is greater than the unkink distance (white), the switch is always unkinked. When the distance is smaller than the kink distance (blue), the switch is always kinked. The status of the switch is uncertain in between switching states (light gray) and depends on the previous state and movement. The data shown in the image is the mean of the value in 5 repeated tests with the same tube. The error bar is not shown because the standard deviation is less than 0.01, too small to be seen clearly in the graph. (B) Maximum operating pressure as a function of the twisting angle θ and the influence of tube length L_0 . (C) Influence of tube length L_0 on the unkink and kink distances. (D) Influence of tube length L_0 on the hysteresis.

II. DESIGN

A. Operation Principle

Our fluidic switch is a pre-twisted tube mounted on a linear stage. One end of the tube is fixed, whereas the opposite end is both translatable along a linear stage and rotatable about the tube's axial direction. We empirically determined that airflow can be cut off by pre-twisting the elastic tube and then decreasing the distance between the two ends of the tube, where the twisting angle θ changes the torsional load, and the distance D changes the kinking status. This approach only requires linear movement for fluid switching; based on this switching principle, we can program a tube as a switch by setting the pre-twisting angle θ and pre-stretching distance D_0 (Figure 2A). After the programming stage, the twisting angle is fixed, and only the distance D is changeable.

The pre-twisted tube has two states: unkinked state (open,

Figure 2B) and kinked state (closed, Figure 2C). In the initial state, D is equal to the tube length L_0 ; the tube segment has not been stretched or twisted. After programming, when the distance D is larger than the unkink distance D_{unkink} , the tube is in an unkinked state and airflow can pass. When the distance D is smaller than the kink distance D_{kink} , the tube changes into a kinked state and airflow is blocked. The kink D_{kink} and unkink D_{unkink} distances are different; there is a hysteresis between the two states, allowing for well-defined switching points.

B. Characterization

To evaluate the switching behavior of our pre-twisted tube, we choose pre-twisting angles θ and tube lengths L_0 as key parameters, and investigate their corresponding relationships to kink (D_{kink}), unkink (D_{unkink}), and hysteresis ($D_{unkink} - D_{kink}$) distances, as well as the maximum

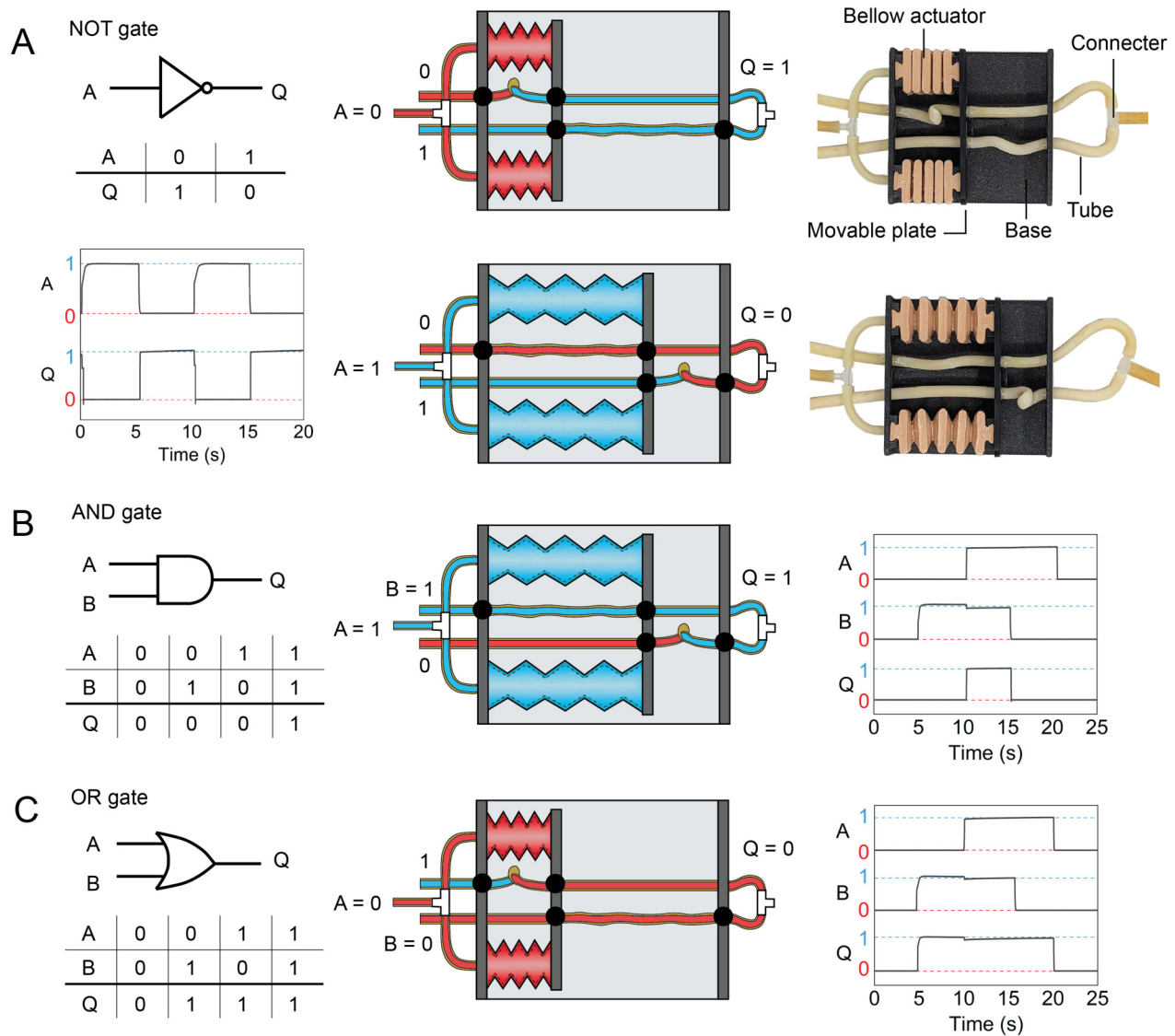


Fig. 4. **Implementation of a complementary switch and fluidic logic gate configurations.** (A) Truth table, pressure metrics, schematic representation, and experimental setup of a NOT gate. Two bellow actuators manipulate the movable plate along a guide rail, altering the lengths of two pre-twisted tubes. Black circles denote the mounting points on the base and movable plate. In the data plot, 0 represents the atmospheric pressure (0 kPa) and 1 represents 110 kPa. (B) Truth table, schematic diagram, and pressure readings for an AND gate. (C) Truth table, schematic outline, and pressure data for an OR gate.

pressure P_{max} that can be cut off. Our experiments are based on a rubber tube with an inner diameter of $1/16$ inch and an outer diameter of $3/16$ inch (McMaster Carr 5234K405). We mounted the tube to 3D-printed mounting plates using super glue. The input and output pressures were measured with SSI Technologies Digital Pressure Gauge (MGA-300-A-9V-R).

The pre-stretch distance D_0 was set to $1.5 \times L_0$ to ensure the tube remains in an unknicked state throughout the programming (pre-twisting) stage, while also mitigating the risk of tube rupture due to overstretching. For twisting angles $\theta < 6\pi$, in this tube configuration, and as indicated by the dark grey area in **Figure 3A**, the tube either deforms into a ring shape without forming an impermeable kink, or produces a kink that cannot withstand an operating pressure

of $50kPa$. For a fixed tube length, generally, the kink and un-kink distances increase with the twisting angle (**Figure 3A**). The maximum pressure a twisted tubing can block (i.e., its operating pressure), increases with the twisting angle as well (**Figure 3B**). A short tube length for a given twist, allows for higher operating pressures when compared to longer tubing. Due to safety concerns from potential connector disengagements, the maximum pressure measurable in our setup was limited to $280 kPa$.

We empirically tested the impact of tube length L_0 on kink, unkink, and hysteresis distances (**Figure 3C, D**). The longer the tube, the greater the twisting angle required to achieve an impermeable kink. The hysteresis distance decreases with an increase in twisting angle, but once the twisting angle reaches a threshold value, the hysteresis dis-

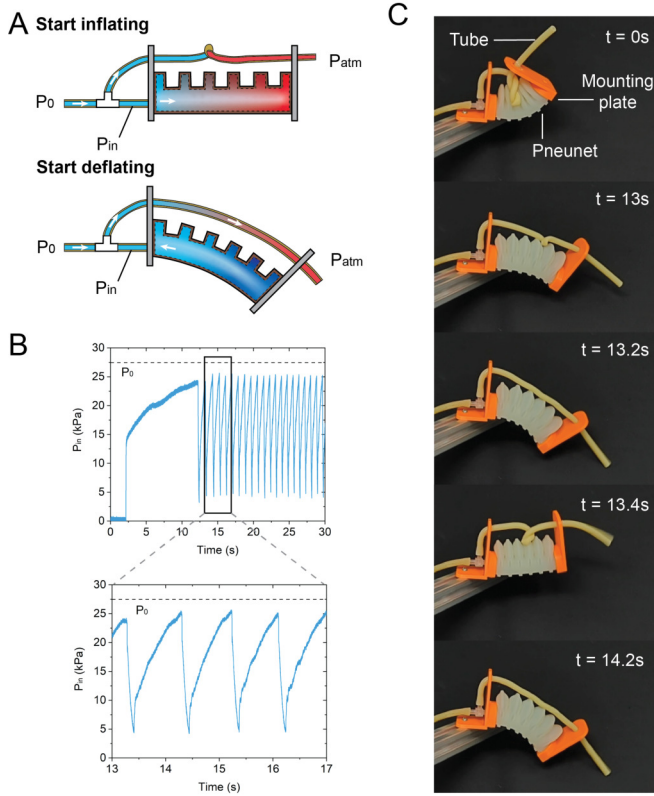


Fig. 5. **Pre-twisted tube used as a distance sensor for the oscillatory control of a PneuNet** (A) Schematic of the setup. By mounting the pre-twisted tube onto a PneuNet, the tubing initially kinks, allowing for pressure buildup inside the PneuNet. When the PneuNet bends beyond d_{unkink} , it depressurizes against the atmosphere. (B) Oscillatory signal generated by the sensorized PneuNet. The preset input pressure P_0 is 27 kPa and is controlled by a pressure regulator. At this input pressure, the PneuNet oscillates at a frequency of 1.12 Hz. (C) Inflation stages of the sensorized PneuNet.

tance increases instead. For a 4cm long tube, the hysteresis distance trend depicts an exception; we hypothesize that small tube lengths, and small twisting angles lead to kinking behaviors that are combinations of twisting and folding methods.

III. DEMONSTRATION

A. Fluidic logic gates

Since the on-off states of our pre-twisted tubing are directly controlled via a uniaxial change in distance, linear pneumatic actuators can be employed for switching (Figure 4). By programming tubes with different twisting configurations, a CMOS-equivalent switch can be implemented. We showcase NOT-, AND-, and OR-gate configurations. At any given time, one out of two twisted tubes is kinked, allowing for complementary fluid switching. The input and output pressure were measured with Panasonic ADP5151 pressure sensors and a NI USB-6009 Multifunctional Data Acquisition Module 779026-01 DAQ.

B. Oscillating actuator

Our twisted tubing can also be used as a distance sensor; when a critical distance (D_{unkink}) is exceeded, the twisted

tubing can act as a pull-down resistor, deflating an otherwise inflating pneumatic network (or PneuNet). This configuration allows the PneuNet to oscillate as it bends until it reaches D_{unkink} , and then contracts due to being connected to atmospheric pressure (Figure 5, Video 1). The oscillating signal can also be used to control many other soft robotic systems [12, 24, 25].

IV. DISCUSSIONS

A. Elastic force and torque from twisting

Although the pre-twisted tube can switch high-pressure signals, the output torques from twisted tubes need to be taken into consideration when used as a valve or a sensor. In our complementary switch design, two bellows actuators and a linear guide are used to overcome the torque. When the pre-twisted tube is used for other applications, overcoming the force along the axial position and the torque around the axial position will become crucial.

B. Programmability

The switching (kink/unkink) distance, hysteresis, and maximum operational pressure of the pre-twisted tube change with the tube length and pre-twisting angle. Additional rotary actuators could be used to tune the twisting angle of a twisted tube, and therewith manipulate its switching behavior.

C. Choice of tube

In this paper, we have shown the fluid-switching capability of a pre-twisted tube based on a specific rubber tube, but not all elastic tubes have the same properties; the material and geometric parameters (i.e., inner and outer diameters) of the tube impact the switching behavior. Some tubes cannot be configured as a pre-twisted, tube-based switch. We currently recommend applying our characterization method to any new tubing you may choose to explore this concept. A follow-up study could explore different tubes and their affinity to being configured as a fluid switch.

V. CONCLUSION

We introduced a new twisting-based method for switching airflows under high pressure (≥ 280 kPa), and analyzed the influence of tube length and twisting angle on the kinking behavior. By pre-loading a torsional load onto tubing via twisting, only an uniaxial distance change is required to switch airflows. We showcased a complementary switch from normally-open and normally-closed twisted tubes, and its configuration as NOT-, AND-, and OR-gates. We also demonstrate the use of twisted tubing as a distance sensor for the oscillatory control of a PneuNet with an oscillation frequency of 1.12 Hz.

Among the three kinking techniques used for the manipulation of fluidic signals in soft robots (pressing, folding, and twisting tubes), pre-twisted tubes present the most versatile technique: the twisting angle and tube distance allow for a range of kink and unkink distances as well as hystereses.

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