



Reprogrammable, intelligent soft origami LEGO coupling actuation, computation, and sensing

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Tightly integrating actuation, computation, and sensing in soft materials allows soft robots to respond autonomously to their environments. However, fusing these capabilities within a single soft module in an efficient, programmable, and compatible way is still a significant challenge. Here, we introduce a strategy for integrating actuation, computation, and sensing capabilities in soft origami. Unified and plug-and-play soft origami modules can be reconfigured into diverse morphologies with specific functions or reprogrammed into a variety of soft logic circuits, similar to LEGO bricks. We built an untethered autonomous soft turtle that is able to sense stimuli, store data, process information, and perform swimming movements. The function multiplexing and signal compatibility of the origami minimize the number of soft devices, thereby reducing the complexity and redundancy of soft robots. Moreover, this origami also exhibits strong damage resistance and high durability. We envision that this work will offer an effective way to readily create on-demand soft robots that can operate in unknown environments.

INTRODUCTION

The seamless integration of actuation, computation, and sensing as exhibited by biological systems has long served as a source of inspiration for systems engineering. Imparting such capabilities to a single soft module enables various soft robots to readily be reconfigured to accommodate unknown situations. However, current advances have focused largely on individual components rather than multifunctionality integration. For example, a variety of novel soft actuators have been reported, ranging from fluidic actuators,^{1–4} dielectric elastomers,^{5,6} liquid crystal elastomers,⁷ hydrogels,⁸ and magnetic actuators,⁹ to shape memory polymers.¹⁰ In the field of soft controllers, soft components with embedded computation capability possess the ability to convert one constant input signal to multiple oscillatory output signals.^{11–16} Advances in flexible sensors have expanded sensing capabilities to the detection of strain,¹⁷ pressure,¹⁸ temperature,¹⁹ sweat,²⁰ and odor²¹ using soft materials. With the current development in these fields, researchers such as Drotman et al.¹¹ have successfully assembled independent soft actuators, oscillators, and sensors into autonomous soft robots. Despite significant progress, the actuation, computation, and sensing capabilities of soft robots still depend on different components, which results in bulky systems, intricate fabrication processes, and poor reconfigurability.

An effective approach to solving these challenges is to implant computation and sensing capabilities into soft actuators. A variety of promising strategies, such as kirigami,^{22,23} origami,^{24,25} nonlinear actuators,^{26–28} and viscous flow^{29,30} have been harnessed to encode physical intelligence into soft materials and to program the actuation sequences of soft robots. Nonetheless, the intelligence and morphing enabled by these strategies are usually preprogrammed and can hardly be altered during in-life service, limiting the application of these robots in unstructured environments. In addition, soft sensors can be attached to an actuator surface or embedded into the actuator body.^{31–35} These sensors detect external stimuli by measuring variations in resistance,^{31,32} capacitance,³³ light power,³⁴ and magnetic fields.³⁵ However, the sensing signals generated are typically incompatible with the control signals of the aforementioned soft control devices. As a result, electronic conversion circuits are needed to bridge the difference between signals. Therefore, coupling actuation, computation, and sensing in an efficient, programmable, and compatible way has been an endless pursuit of researchers.

Biological systems have evolved to satisfy multiple needs with a single composite, for example, protein, which is the physical basis of organisms, is a typical

example of multifunctionality. Even the same proteins are capable of exhibiting different functions, such as maintaining cell shape, catalyzing biochemical reactions, and ferrying nutrients across membranes. Inspired by these lessons, we present a reprogrammable intelligent soft origami (ReISO) that is endowed with integrated actuation, computation, and sensing. The origami is reconfigurable in morphology and reprogrammable in intelligence through a combination of multifunctionality and plug-and-play design, similar to LEGO bricks. Various function architectures, ranging from twisting, contraction, and bending to radial movement configurations, can be rapidly assembled with unified origami modules. Similarly, fundamental combinatorial and sequential logic circuits and complex functional circuits were also constructed. In addition, the strong damage resistance, high durability, low cost, and easy fabrication of the soft origami allow it to be easily mass-produced. Finally, we fabricated an untethered autonomous soft turtle that was capable of responding to environmental stimuli with only a soft control circuit. Soft actuators and sensors were fused into this circuit without introducing additional soft devices, which was realized via the signal compatibility and function multiplexing strategy of the origami.

RESULTS

Working principle of ReISO

Soft origami. The ReISO design is based on the Kresling origami,^{25,36–38} which is a triangulated hollow cylinder. As illustrated in Figures 1A and 1B, the Kresling origami comprises two square panels for its upper and lower surfaces and eight triangular panels for its sides. When subjected to clockwise (CW) torque, this origami folds along its four inclined creases (the red dotted lines in Figures 1A and 1B), yielding a twist-contraction movement. Similarly, the ReISO possesses four slanted grooves, which function in the same way as the creases of the Kresling origami and split the square side into two triangular panels. The whole structure is a cubic airtight chamber, with one control tube inserted into it and one intelligent tube passing through it (Figures 1C and 1I). The plug-and-play male and female connectors are located on the upper and lower surfaces of the ReISOs to facilitate their assembly/disassembly, as shown in Figure S3.

Actuation capability. As shown in Figures 1C and 1D, when vacuum pressure is applied to the chamber via the control tube, the two triangular panels on the same side fold along the slanted groove. The simultaneous folding behavior on all four sides triggers a compound deformation that couples twisting and contraction. The ReISO is able to twist CW or anticlockwise (ACW), and its twisting direction is determined by the inclined direction of the slanted grooves, resembling the Kresling origami (Figure S4; Video S1). The twisting angle and contraction stroke increase with increased vacuum power, demonstrating the deformation controllability of the ReISOs (Figure S5). Furthermore, the soft origami has a fast response time of approximately 0.20 s (CW twisting) and 0.18 s (ACW twisting) to reach its deformed state (90% of the maximum twisting angle), as depicted in Figure S6.

Computation capability. It should be noted that this soft origami possesses computation capability, which is realized through the intelligent tube and capillary tube (Figures 1I and 1J). A ReISO consists of three logic ports: input port A, source port S, and output port Q. S and Q are the two ends of the intelligent tube. The capillary tube connects the output port Q with the atmosphere. In this work, we define the atmospheric pressure and vacuum pressure as the fluidic signals 0 and 1, respectively. When the origami is in its original state (the input port A is connected to the atmosphere), the intelligent tube in the chamber is straight and air flows freely through it (Figure 1I; Video S2). The source port S and output port Q are in the same pressure state (vacuum pressure). When the origami is actuated (the input port A is connected to vacuum pressure), the intelligent tube is kinked and becomes V-shaped, and the airflow is blocked

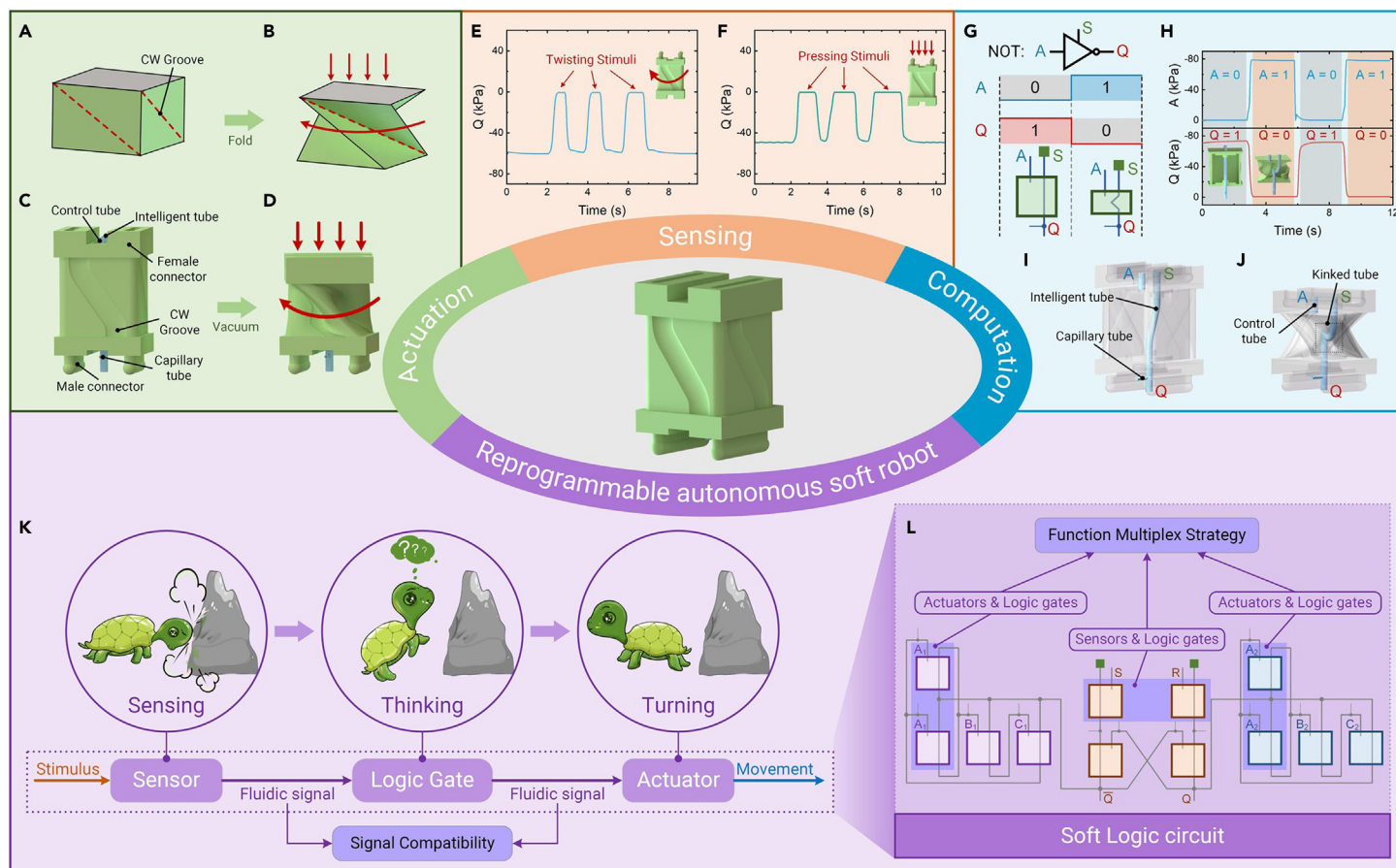


Figure 1. Reprogrammable intelligent soft origami (ReISO) with embedded physical intelligence (A and B) The clockwise Kresling origami is in unfolded (A) and folded (B) states. The red dashed lines represent the creases. The red arrows indicate the folding direction of the Kresling origami. (C and D) Schematic illustration of the clockwise ReISO in unfolded (C) and folded (D) states. The grooves in the sides denote the creases of the soft origami. (E and F) The pressure response of the ReISO when twisting stimuli (E) and pressing stimuli (F) are applied to it. (G) The ReISO is equivalent to a NOT logic gate. The bottom figure is the truth table of the soft NOT logic gate. A, S, and Q are the input port, source port, and output port, respectively. The green block represents the vacuum pressure. (H) The pressure response of the ReISO. The S port is connected to a constant vacuum pressure of -80 kPa. The atmospheric pressure is defined as fluidic signal 0, and the vacuum pressure is defined as fluidic signal 1. (I and J) The intelligent tube is in straight (I) and kinked (J) states. (K) An autonomous soft turtle built solely with ReISOs is able to sense, think, and move. The signal transmission between soft sensors, logic circuits, and actuators is enabled through fluidic signals. (L) The soft control system of the turtle. The modules in the pinkish-purple boxes are multiplexed as 2 functional components.

due to the axial force exerted on the intelligent tube (Figure 1J). The pressure state of the output port Q is converted from vacuum pressure to atmospheric pressure via the capillary tube. In this way, the soft origami converts the fluidic signal 1 to 0 or converts 0 to 1, which is the same function as a NOT logic gate (Figures 1G and 1H). The blocking behavior of ReISO also works with pressurized air, as shown in Figure S7. In this case, both the vacuum pressure and positive pressure are represented as 1.

Sensing capability. In addition to actuation and computation capabilities, soft origami exhibits a sensing capability, which is realized with the intelligent tube and capillary tube. Origami deformations can be obtained by measuring the pressure changes at port Q. As demonstrated in Figures 1E and 1F; Video S3, when the origami was twisted or pressed, the pressure at port Q increased owing to the kink of the intelligent tube. After releasing the mechanical stimuli, the pressure at port Q decreased.

As illustrated in Figures S20A and S20B, the pressure at port Q increases with an increase in the twisting angle α and compression L_c , and a nonlinear relationship between them can be observed. The ReISOs have a measuring range of 20° – 65° for twisting angle and 1 – 10 mm for compression, respectively. In addition, they exhibit low hysteresis between the deformation and release processes.

A continuous fatigue test of twisting and compressing the ReISOs for 3,000 cycles was carried out (Figures S20C and S20D). The ReISOs exhibited consistent sensing capability, and no failures or permanent changes were observed during the testing, which suggests that the ReISOs had excellent durability and repeatability.

The deformation of the origami is measured as fluidic pressure signals, which are compatible with the actuation signals of fluidic actuators and the control signals of fluidic circuits (Figure 1K). Therefore, it is possible to fuse actuation,

computation, and sensing functions within a soft intelligent system that is composed solely of ReISOs (Figure 1K). Furthermore, the function multiplexing strategy, in which a single ReISO can act as two soft components in one soft machine (Figure 1L), substantially reduces the redundancy of soft control systems, as described in detail in the following sections.

Logic characterization of the ReISOs

The computation capability of the origami is enabled via an intelligent tube that passes through the origami; thus, the geometric parameters of the tubes must be chosen carefully. The intelligent tubes have to satisfy two requirements: (1) they cannot be buckled under the vacuum state and (2) they should effectively block the airflow when compressed. To accommodate soft actuators with varying degrees of deformation, it is desirable to minimize the compression stroke (kinking threshold ΔH_{kink}) required to block airflow. This is because a smaller ΔH_{kink} endows the ReISOs with more reliable computation capability. Then, the kinking properties of elastomer tubes with different dimensions were investigated. As depicted in Figure 2A, thinner tubes (internal diameter $\times$ external diameter = 1.5×2.0 mm) collapsed when subjected to vacuum pressure (Figure S23A). Tubes with a size of 1.0×2.0 mm were difficult to be kinked due to their smaller internal and external diameters (Figure S23B). The remaining four types of tubes could be kinked with a compression stroke of less than 9 mm (Figure S23C). Notably, the tubes with a size of 2.0×3.0 mm exhibited the smallest kinking threshold ΔH_{kink} and were used as the intelligent tubes for the ReISOs.

For tubes with the same diameters, the kinking threshold ΔH_{kink} increases as the tube length increases (Figure 2B). When the ReISO is actuated, a torque is also exerted on the tube. We then studied the dependence of the kinking

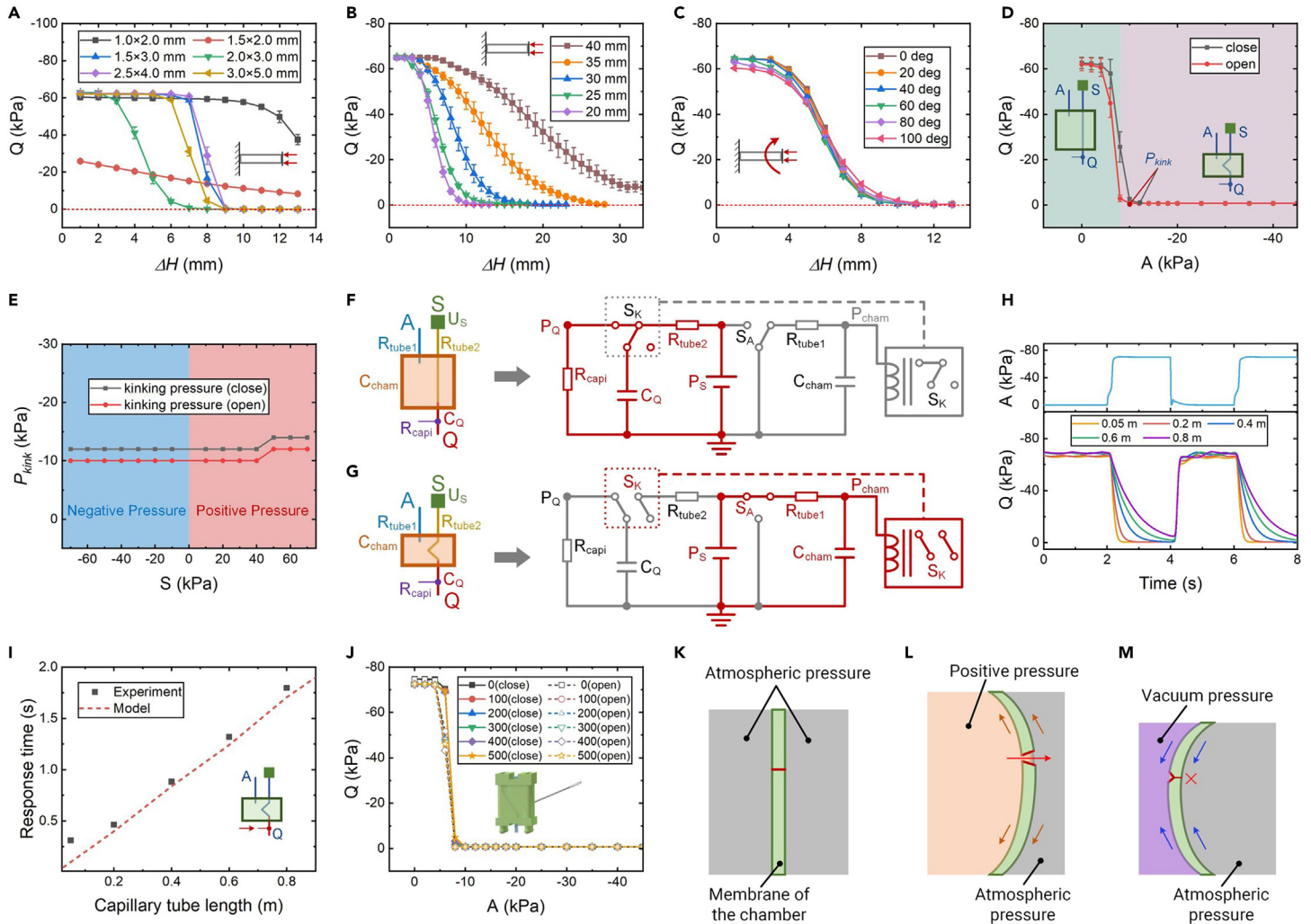


Figure 2. The logic performances of the ReISOs (A) The kinking characterization of elastomer tubes with different diameters. The numbers in the legend represent the internal and external diameters of the elastomer tubes. The unkinked length of these tubes is 20 mm. (B) The kinking characterization of elastomer tubes with different lengths. (C) The influence of the pre-twisted angle of the elastomer tubes on the kinking characterization. (D) The relationship between the pressure at the output port Q and the pressure at the input port A. (E) The relationship between the kinking pressure and the pressure of the source port S. (F and G) The equivalent fluidic circuit of the ReISO in the unfolded (F) and folded (G) states. (H) The influence of the capillary tube length on the pressure response of the ReISOs. (I) The relationship between the capillary tube length and the response time of the ReISOs. (J) The pressure response of the ReISO after it is pricked with a needle. The numbers in the legend represent the number of needle pricks. (K–M) The damage-resistance principle of the ReISOs. The chamber of the ReISO is connected to the atmospheric pressure (K), positive pressure (L), and vacuum pressure (M), respectively. The red line represents the hole pricked by a needle. The orange and blue lines represent tension forces and compression forces, respectively. The error bars in this figure are calculated based on three tests.

threshold on the twisting angle of the soft origami by twisting a tube with a length of 20 mm from 0° to 100°. Interestingly, the kinking threshold shows little variation for different twisting angles (Figure 2C), suggesting that the blocking behavior is mainly attributed to the contraction of the ReISO.

We define kinking pressure P_{kink} as the pressure required to completely block the airflow in the intelligent tube. As shown in Figure 2D, the kinking pressure for closing the airflow is slightly lower than that for opening it. This hysteresis can be attributed to the snapping behavior that occurs during the compression of the tubes.

Furthermore, we investigated the influence of the pressure at the source port S on the kinking pressure. We observed that the pressure at port S had a slight influence on the kinking pressure, even when positive pressures were applied (Figure 2E). Higher positive pressures (≥ 45 kPa) resulted in greater forces applied to the internal surface of the intelligent tube; therefore, a larger compression force (lower vacuum pressure at port Q) is required to kink the tube.

Subsequently, we developed an analytical model to characterize the logic performances of the ReISOs. As shown in Figures 2F and 2G, the ReISO can be equivalent to a fluidic circuit, in which the fluidic pressure (Pa), mass flow rate (kg/s), fluidic resistance (Pa · s/kg), and fluidic capacity (kg/Pa) are analogous to the voltage (V), current (A), resistance (Ω), and capacity (F) of electrical circuits, respectively. Then, the logic response time of the ReISO can be expressed as Equation 1 (the detailed derivation is described in the supplemental information):

$$t_{1 \rightarrow 0} = -R_{capi} C_Q \ln \frac{P_{Q1}}{P_{Q0}} + t_{kink} \quad (\text{Equation 1})$$

where R_{capi} is the fluidic resistance of the capillary tube, C_Q is the fluidic capacity of the airtight channel that connects with port Q when the ReISO is in the folded state, and P_{Q0} is the pressure of port Q in the unfolded state. The state in which the pressure at port Q (P_Q) is higher than P_{Q1} is defined as the logic low state (here, the fluidic signals processed by the ReISO are vacuum pressures; thus, the magnitudes of P_Q and P_{Q1} are negative).

The response time of the ReISO was found to increase with the length of the capillary tube (Figure 2H). The model prediction and experimental data are compared in Figure 2I, where good agreement is illustrated, suggesting that the model could be used as an analytical tool to predict the performances of soft fluidic circuits and to guide the design of future soft robots.

Fluidic soft actuators have persistently been plagued by the threat of leakage, which hampers their functionality and reliability. Here, we carried out damage tests, pricking the origami with a needle repeatedly, to explore its resistance to leakage. The diameter of the needle for the pricking experiments was 0.8 mm. The ReISOs were pricked at different locations on their four side surfaces. As depicted in Figure 2J and Video S4, pricking the soft origami 500 times has a negligible impact on the kinking pressure required to open and

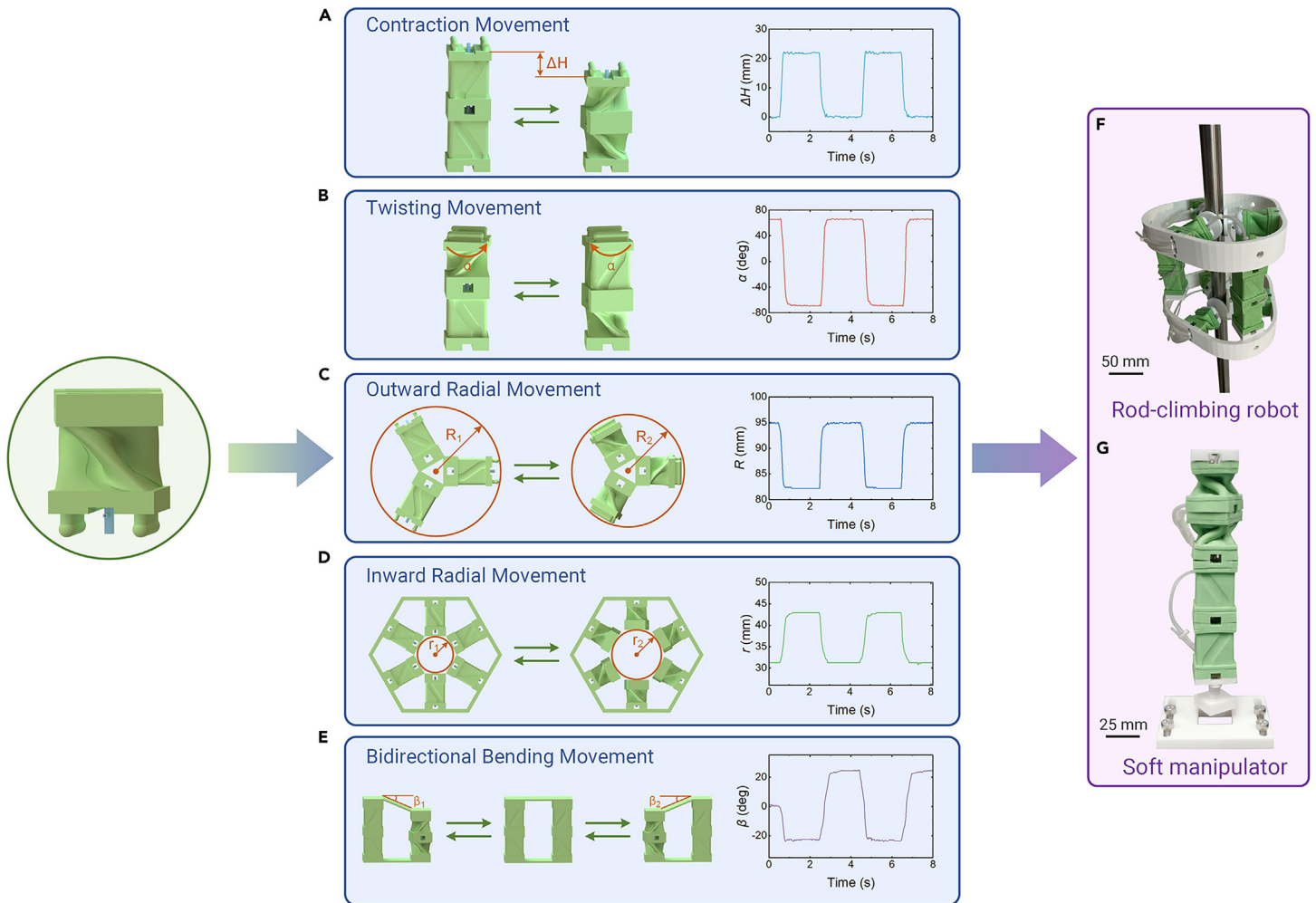


Figure 3. Reprogrammable morphologies of the ReISOs (A) Two ReISOs in the same actuation state form a contraction combination. (B) Two ReISOs in the opposite actuation states form a twisting combination. (C) An outward radial movement is realized by fixing 3 ReISOs in the same actuation state at the center of a circle. (D) An inward radial movement is achieved by fixing 6 ReISOs to a polygon that encircles them and actuating them simultaneously. (E) A bidirectional bending combination is enabled by assembling 2 contraction combinations in the opposite actuation states. (F) A soft rod-climbing robot constructed with the ReISOs. (G) A soft manipulator constructed with the ReISOs.

close the airflow. This excellent leak resistance is attributed to the unique buckling behavior of the ReISOs. As shown in Figures 2K–2M, the positive pressure causes the size of the pinhole to increase owing to the tension forces in the membrane, whereas the vacuum pressure decreases the size of the pinhole due to the compression forces in the membrane. Consequently, our vacuum-powered ReISOs exhibit better leak resistance than do fluidic soft actuators that are driven by pressurized air.

Reconfigurable morphologies

A single ReISO is able to exhibit a compound deformation that couples twisting and contraction movements. This unique characteristic of the ReISO, combined with its plug-and-play connectors, allows for the facile reconfiguration of a vast array of morphologies with specific motion behaviors (Video S5). As illustrated in Figures 3A and 3B, two ReISOs with opposite twisting directions are connected in series, forming a morphology that can perform pure contraction or pure twisting movements. The simultaneous actuation of the two ReISOs counteracts their twisting deformations, resulting in a pure contraction movement. Conversely, actuating one ReISO and releasing the other one counteracts their contraction deformations, which yields a pure twisting movement. When several (three or more, in this case, we use three) ReISOs are evenly distributed along the circumferential direction of a circle and fixed at the center of the circle, their simultaneous actuation produces an outward radial movement (Figure 3C). By fixing these ReISOs (in this case, six modules are used) to a polygon that encircles them, an inward radial movement can be generated, as shown in Figure 3D. Assembling these basic combinations into more complex ones can unlock movements with greater diversity. For example,

two contraction combinations can exhibit a bidirectional bending movement, as demonstrated in Figure 3E.

By using these ReISO-based movement combinations, we successfully fabricated two soft robots that possessed different functions. The first one was a rod-climbing robot, which consisted of two inward radial combinations and a contraction combination, as illustrated in Figure 3F. The inward radial combination allowed the robot to grasp and loosen the rod, whereas the contraction combination offered forward/backward thrust for the robot. This rod-climbing robot was able to climb along a smooth rod at a speed of 2.67 mm/s (Video S6). The second robotic prototype was a soft manipulator capable of placing objects with specific shapes into holes. As depicted in Figure 3G and Video S6, this device was composed of a contraction combination (the upper two modules) and a twisting combination (the lower two modules). The twisting combination adjusted the orientation of the objects so that the objects matched the shape of the holes, and the contraction combination subsequently dropped the objects into the holes. The twisting angle of the ReISOs could be tuned by regulating the actuation pressure, as demonstrated in Figure S5.

Reprogrammable intelligence

Reprogrammable soft combinatorial logic circuits. A single ReISO serves as a NOT gate, which is a functionally complete binary logic gate and is able to construct all the fundamental 1-bit (NOT and Buffer) and 2-bit (NAND, NOR, AND, OR, XOR, and XNOR) logic gates via the assemblage of multiple modules (Video S7). For instance, the Buffer gate is an inverted NOT gate and can be created from a two-module combination (Figure 4A), in which the output port of the first ReISO is connected to the input port of the second ReISO ($A = \bar{\bar{A}}$).



Figure 4. Reprogrammable soft logic circuits of RelSOs (A–C) The soft combinational logic circuits. (A-i) The logic symbol and Boolean expression of the Buffer gate. (A-ii) The schematic of the soft Buffer gate circuit. (A-iii) The pressure traces of the soft Buffer gate. (A-iv) The truth table of the Buffer gate. (A-v) The experimental image of the soft Buffer gate. (B) The NAND gate. (C) The NOR gate. (D and E) The soft sequential logic circuits. (D) The soft ring oscillator circuit. (E) The soft SR latch circuit. (F and G) The soft functional circuits constructed with the above fundamental logic circuits. (F) The soft full adder circuit. (G) The soft frequency divider circuit. The green block represents the vacuum pressure.

The NAND and NOR gates can be expressed using two NOT gates, according to De Morgan's theorems. As shown in Figure 4B, the NAND gate is constructed by connecting the output ports of two RelSOs ($\overline{AB} = \overline{A} + \overline{B}$), whereas the NOR gate is built by connecting the output port of the first RelSO to the source port of the second RelSO ($\overline{A+B} = \overline{A}\overline{B}$; Figure 4C). The AND gate and OR gate are the inver-

sions of the NAND gate and NOR gate, respectively. Thus, they can be obtained by combining the NAND gate and NOR gate with a NOT gate ($AB = \overline{\overline{AB}}$, $A+B = \overline{\overline{A+B}}$), respectively (Figures S14A and S14B). Similarly, XOR and XNOR gates can be built with six NOT gates ($A \oplus B = \overline{AB} + \overline{A}\overline{B}$, $A \odot B = \overline{\overline{AB} + \overline{A}\overline{B}}$), as shown in Figures S14C and S14D.

Reprogrammable sequential logic circuits. In addition to combinatorial logic circuits, sequential logic circuits can also be realized with ReISOs. Unlike combinatorial logic circuits, which rely only on present inputs to generate outputs, sequential logic circuits depend on both present and past inputs to generate outputs.

A ring oscillator is a sequential logic circuit that is able to “process” input signals. As shown in Figures 4D–i, it is created by connecting an odd number of NOT gates as a loop, with the output of the last NOT gate fed back into the first one. Then, the last output is the logical NOT of the first input due to the odd number of NOT gates. In Figures 4D–ii, we used three ReISOs to build a soft ring oscillator. When the source ports of the three ReISOs were connected to a constant vacuum pressure, the loop connection enabled the three ReISOs to oscillate spontaneously and sequentially between their unfolded and folded states (Video S8). The working principle of the soft ring oscillator is described in the supplemental information. As a result, the constant pressure was converted into multiple (odd numbered) oscillatory pressures, verifying the signal processing capability of ReISOs.

The SR latch is a logic circuit with a 1-bit memory and is able to “store” previous input values. As shown in Figures 4E–i, this circuit accepts two inputs (S and R) and provides two complementary outputs (Q and $\bar{Q}$). The input S will SET the device (meaning the output Q = 1), whereas the input R will RESET the device (meaning the output Q = 0). In Figures 4E–ii, we used two cross-coupled NOR gates to build an SR latch, in which the output of one NOR gate is fed back to the input of the other one and vice versa. As shown in Figures 4E–iii and 4E–iv and Video S8, setting the input S to 1 switched the output Q to 1, which remained 1 even after the input S was returned to 0, functioning as a memory device. Likewise, setting the input R to 1 switched the output Q to 0, which maintained 0 after the input R was returned to 0. Therefore, this soft circuit is able to remember previous input signals and exhibit memory functionality.

Furthermore, we also constructed a soft JK flip-flop circuit and a soft D flip-flop circuit to exhibit the capability of the ReISOs in reprogramming sequential logic circuits. These circuits are described in the supplemental information and Figure S16.

Reprogrammable soft functional circuits. With these basic logic circuits, any higher-level functional logic circuits could, in principle, be programmed by harnessing the foundations of canonical Boolean functions and their algebraic combinations. To verify this capability, the implementation of a soft full adder and a soft frequency divider is taken as an example (Figures 4F and 4G; Video S9).

As illustrated in Figures 4F–i, a full adder is an arithmetic circuit that contains three inputs, namely, A, B, and C_{in} (carry input), and two outputs, C_{out} (carry output) and S. The two outputs can be expressed with the fundamental logic gates mentioned above: $S = C_{in} \oplus (A \oplus B)$, $C_{out} = AB + C_{in}(A \oplus B)$. (The Boolean operation symbols are depicted in Figures 4A–4C and S14) Next, the soft full adder was fabricated by assembling 21 ReISOs and connecting them according to the logic circuit shown in Figure 4F–ii. All eight addition computations possible for the full adder were experimentally validated (Figures 4F–iii and 4F–iv; Video S9), demonstrating the number operation functionality of ReISOs. The soft frequency is described in the supplemental information.

Autonomous and reconfigurable soft robots

Reconfigurable soft robots with built-in intelligence. As shown in Figures 5A and 5B, we built a soft robotic turtle that is made up of five ReISOs, a miniature vacuum pump, and a lithium battery. The ReISOs with the same label are connected; thus, they are always in the same actuation state and same logic state. In this robot, the two ReISOs connected with the front legs of the turtle are labeled C, the two ReISOs connected with the hind legs are labeled B, and the ReISO in the center of the robot body is labeled A. The five ReISOs form a soft ring oscillator circuit composed of three NOT logic gates, which acts as the soft controller of the turtle (Figure 5C). This controller converts the constant pressure generated by the vacuum pump into three oscillatory pressures, causing the five ReISOs to fold and unfold periodically. Consequently, the four ReISOs connected with the legs of the turtle also serve as actuators: they generate the rhythmic swinging of the legs. The swinging speed during the folding process is faster than that during the unfolding process (Figure 5D). Therefore, the thrust generated during the folding process is larger than that during the unfolding process (the operation principle is described in the supplemental information), driving

the turtle to rhythmically move forward. The soft turtle can be reprogrammed to swim forward, backward, CW, and ACW by reconfiguring modules B and C (Figures 5F–5I; Video S10, the orange lines in Figures 5F–5I represent the twisting direction of the modules). The swimming and rotating speeds that the soft turtle can reach are 24.65 mm/s (5.4 body length/min) and 7.77°/s, respectively.

Autonomous soft robots. To adapt to the dynamic and unstructured environment, soft robots are also required to sense external stimuli and perform multiple movement gaits. Then, the sensing capability of the ReISO is introduced into the soft turtle (Figure 6A). It should be noted that, when acting as a soft sensor, the ReISO is able to output fluidic signals, which are compatible with the control system described above (Figure 1K). We constructed a more advanced soft turtle that was capable of sensing stimuli, storing data, processing signals, and actuating muscles using only ReISOs. As illustrated in Figures 6B and 6C, the turtle consists of an SR latch circuit and two ring oscillator circuits, with the source ports of the two ring oscillators connected to the output ports of the SR latch ($\bar{Q}$ and Q). The SR latch circuit is responsible for sensing external stimuli and storing data, whereas the two ring oscillator circuits convert the constant pressure from the output ports of the SR latch circuit to oscillatory pressures. Meanwhile, ring oscillator 1 is connected to the hind legs to enable backward swimming, and ring oscillator 2 is connected to the front legs to enable forward swimming. The SR latch circuit ensures that only one ring oscillator is activated at a time, resulting in the swinging motion of a single pair of legs in the water. It is interesting to note that the number of soft devices required to actuate this soft turtle was minimized because the soft sensors and actuators were integrated into the SR latch circuit and ring oscillator circuits, respectively, which is the function multiplexing strategy of ReISOs (the green area in Figure 6B).

As depicted in Figures 6D, 6E, and S17A–S17C and Video S11, when the module S was subjected to a CW torque ($>0.087 \text{ N} \cdot \text{m}$, illustrated in Figure S22), the turtle detected this torque stimulus. Then, the output Q of the SR latch circuit (the orange circuit in Figure 6B) was set to 1 (in this state, the module $\bar{Q}$ is in the folded state), providing vacuum power for ring oscillator 2. Releasing the CW torque did not change the state of Q because the previous state was stored in the SR latch circuit. The logic high state of Q allowed the two front legs to be actuated by the module A_2 of ring oscillator 2 (the blue circuit in Figure 6B), and the turtle began to swim forward. Likewise, when the ACW torque was applied to the module R, the output $\bar{Q}$ became a logic high state and the turtle began to swim backward by the ring oscillator 1 (Figures 6E, 6F, and S17D–S17F). The stimuli sensing and data storing capabilities enabled the soft turtle to repeatedly switch between movement gaits. The stimuli type and data capacity could be increased further by reconfiguring the soft control system, thereby exhibiting more abundant movement gaits.

DISCUSSION AND CONCLUSION

In summary, a ReISO capable of actuating, computing, and sensing was proposed and characterized. This multifunctionality, combined with the modularity, endowed the ReISO with reconfigurable morphology and reprogrammable intelligence. A variety of motions including but not limited to contraction, twisting, bending, and radial motions was readily obtained and reconfigured. Using the embedded intelligence, we constructed a series of fundamental combinatorial logic circuits (NOT, Buffer, AND, OR, NAND, NOR, XOR, and XNOR) and sequential logic circuits (ring oscillator, SR latch, JK flip-flop, and D flip-flop). Next, a soft full adder and a soft frequency divider were presented to demonstrate the potential of the ReISO in building complex functional circuits. Moreover, this soft origami also featured high durability, low cost, easy fabrication, and strong damage resistance. The function multiplexing and signal compatibility of the ReISOs made it possible to build efficient and intelligent soft machines. As a proof of concept, an untethered autonomous soft turtle that was able to sense stimuli, store data, process information, and perform swimming movements was developed. We believe that the concept presented in this work will inspire and enable more intelligent soft robots with specialized functions and improved environmental adaptability.

Autonomous soft robots with built-in intelligence have attracted tremendous research interest recently. Compared with previous work, our ReISOs have several distinctive advantages, as listed in Table 1.

- (1) Previous work^{11–15,39–43} focuses on developing various soft control components for soft robots. These components are then combined

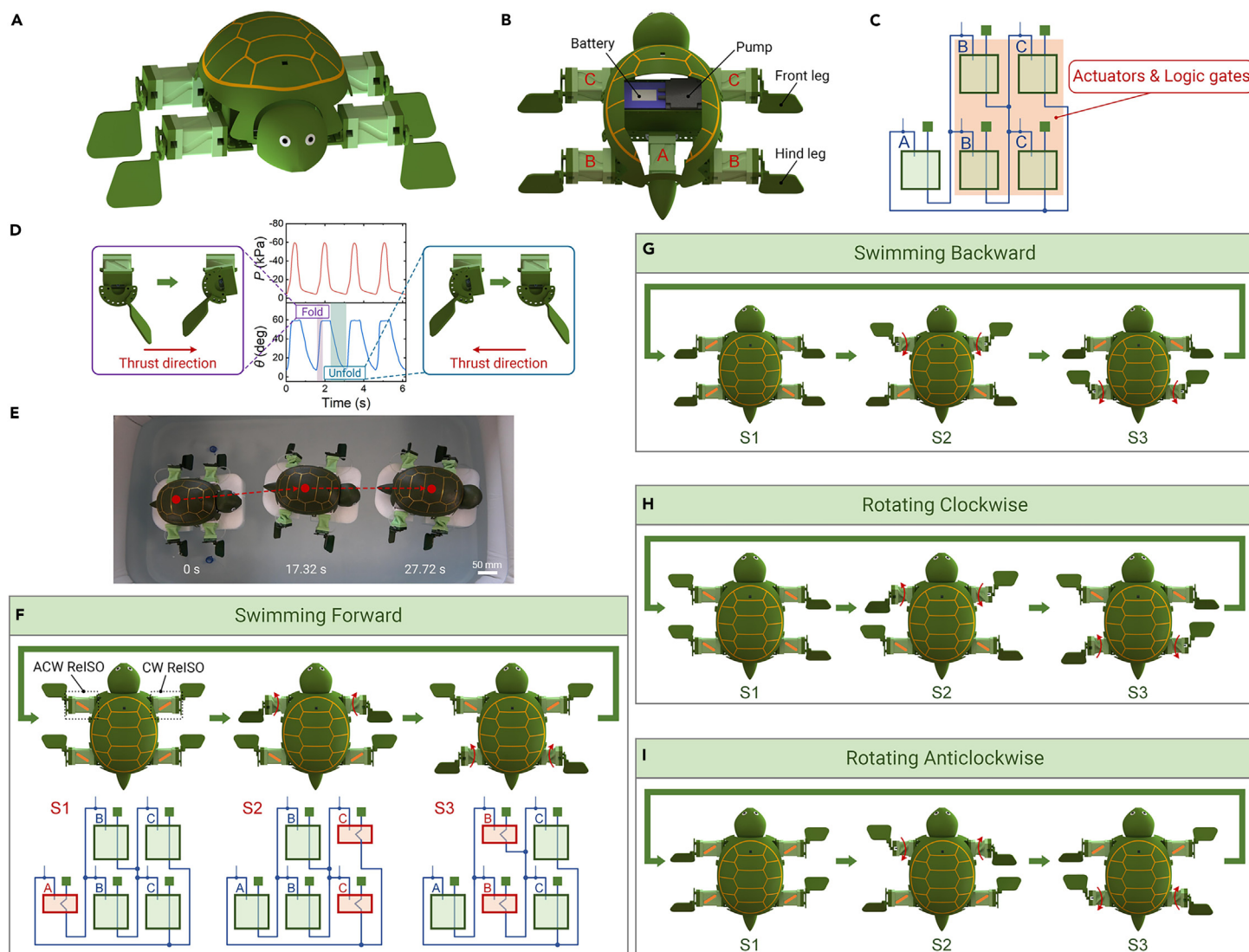


Figure 5. Reconfigurable soft turtle with built-in intelligence (A) Schematic illustration of the soft turtle. (B) The actuation system of the soft turtle. (C) The soft control circuit of the robotic turtle is a ring oscillator with 3 NOT gates. The RelSOs in the red area function as actuators and logic gates simultaneously. (D) The locomotion principle of the soft turtle. The curves are the pressure and twisting angle variations of the soft leg. (E) A sequence of images of the untethered soft turtle swimming forward in a tank. (F–I) The schematic actuation system of the soft turtle when it swims forward (F), backward (G), CW (H), and ACW (I). These motion modes can be readily achieved by reconfiguring RelSOs.

with additional soft actuators that are specifically designed to build soft robots. Unlike these strategies, we implanted physical intelligence into modular soft actuators to render them new functionalities that are rarely achieved in traditional soft actuators, including computation and sensing. The two additional functionalities are effectively enabled by adding an intelligent tube and a capillary tube, which satisfies two requirements with a simple structure and has no influence on the deformation of the actuator. The multifunctionality enables soft robots to sense stimuli, store data, process information, and actuate muscles using only RelSOs. This capability is especially advantageous in reconfiguring on-demand soft machines to adapt to unpredictable environments. When the RelSOs act as actuators, logic gates, and sensors, their input/output signals are the fluidic type (Figure 1K), sidestepping the signal incompatibility that exists in current intelligent soft robots. The compatible communication and integrated multifunctionality eliminate the need for additional microcontrollers, valves, and sensors, thereby decreasing the overall complexity of the autonomous soft robots with embedded intelligence. Furthermore, this multifunctionality integration strategy can readily be generalized to other fluidic actuators, accelerating the development of smart actuators.

- (2) Although the soft-legged quadruped robot designed by Drotman et al.¹¹ is also able to respond to sensor input and switch movement gaits, it requires an additional soft sensor and four additional soft

legs with three pneumatic chambers, which are larger than the soft control system. This robot can only switch its movement gait once, because only one sensor (a bistable valve) is introduced into the control system. By comparison, our soft turtle can respond to sensor input and switch movement gaits without additional soft components via the function multiplexing strategy. This strategy permits a single RelSO to perform multiple functions at the same time. For example, the modules S and R of the turtle function as soft sensors and logic gates simultaneously. The modules A₁ and A₂ act as actuators and logic gates simultaneously (Figures 6B and 6C). Consequently, the soft turtle only requires a control system (an SR latch circuit and two ring oscillator circuits) to achieve the same function as the soft-legged quadruped robot.¹¹ In addition, our soft turtle is able to switch movement gaits repeatedly via the data storing capability enabled by the SR latch circuit.

- (3) Soft robots with both reconfigurable architectures and reprogrammable intelligence can be realized using the RelSOs. These modules can be assembled into different morphologies, allowing their compound deformation to be decoupled into pure twisting and pure contraction, or to be combined into other complex deformations. This reconfigurability widens the range of the possible movements that RelSOs can exhibit, permitting them to be configured as various soft robots to adapt to dynamic environments. The reprogrammable

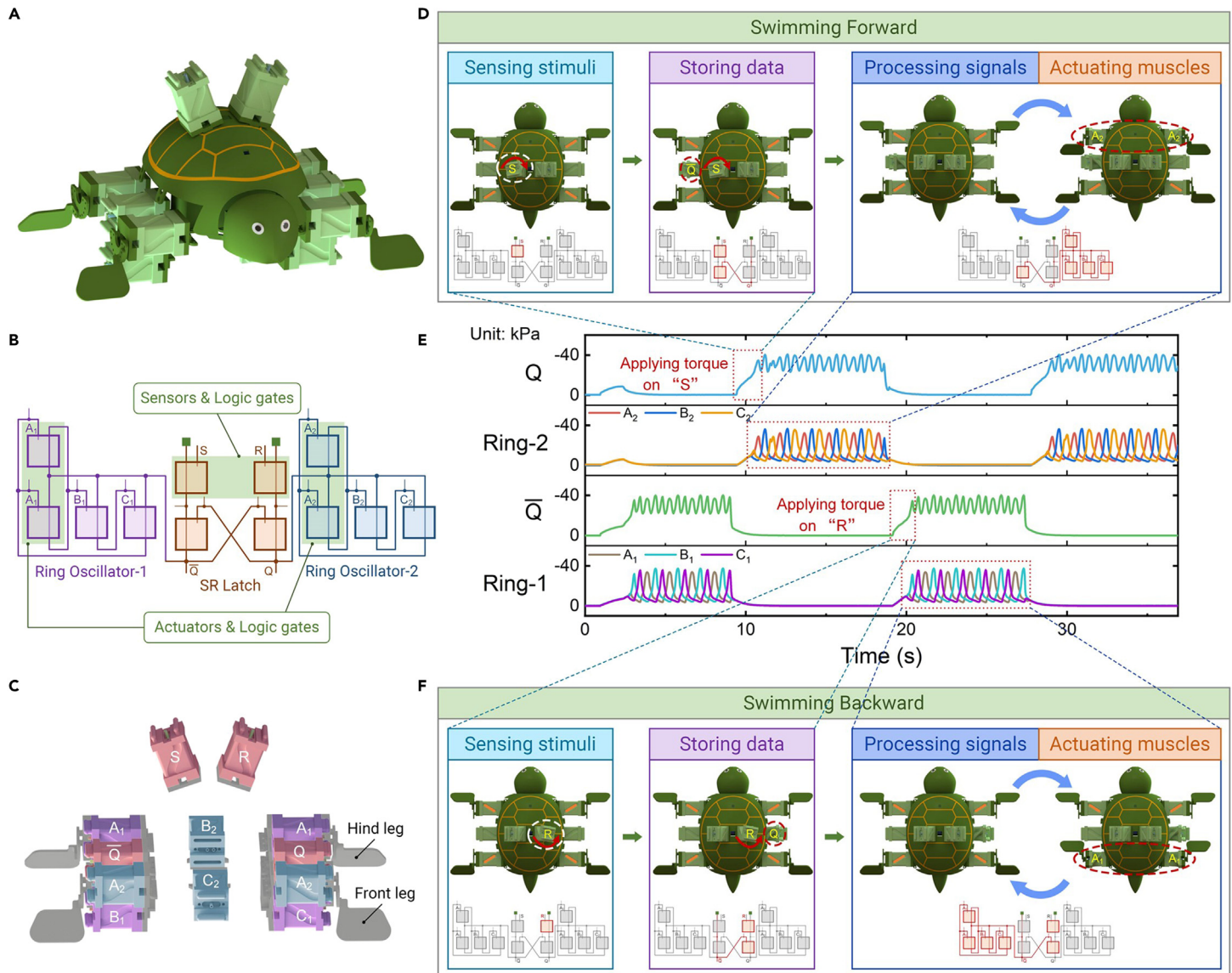


Figure 6. An untethered and autonomous soft turtle that is able to sense stimuli, store data, process signals, and perform swimming movements (A) Schematic illustration of the soft turtle. (B) The soft control system of the robotic turtle is composed of 2 ring oscillator circuits and an SR latch circuit. The ReISOs in the green area function as 2 components simultaneously. (C) The soft turtle was controlled and actuated with 12 ReISOs. The ReISOs with the same color belong to the same subcircuit. (D) The soft turtle switched to forward movement gaits after sensing a CW twisting stimulus. The SR latch circuit detected this stimulus and stored the current state in the circuit even if the stimulus was removed. The ring oscillators then converted the constant pressure from the output ports of the SR latch to oscillatory pressures, which were used to actuate the legs to swing in the water. The bottom figures are detailed information on the soft control system and are clearly depicted in Figure S17. (E) The pressure traces of the soft turtle. Q and $\bar{Q}$ represent the output pressure of the SR latch circuit. Ring-1 and Ring-2 denote the output pressures of ring oscillator 1 and ring oscillator 2. (F) The soft turtle switched to backward movement gaits after sensing an ACW twisting stimulus.

intelligence means that the ReISOs can be used to construct various soft combinatorial and sequential logic circuits. These circuits endow soft machines with the ability to switch between movement gaits according to external stimuli, execute number operations, and divide signal frequency. Similarly, other advanced functionalities, such as the soft counter, which stores the times a particular event has occurred, can also be achieved by reprogramming logic circuits. Furthermore, the plug-and-play connectors enable ReISOs to be readily assembled and disassembled, further enhancing their reconfigurability and reprogrammability.

- (4) The ReISOs are standardized components, just like LEGO blocks. This modularity is especially advantageous in testing soft machines with new configurations, repairing/replacing damaged modules, and rapidly reconstructing soft machines in unstructured environments. In addition, the ReISOs can be fabricated via elastomer casting or liquid crystal display printing, which decreases their fabrication difficulty and cost. The multifunctionality, simple structure, easy fabrication, high durability, and low cost allow ReISOs to be produced in large quanti-

ties. Finally, the modular ReISOs have the potential to be used as commercial educational outfits for robotics learning.

- (5) Current soft control devices^{11–15,39–43} are typically actuated with positive pressure, which tends to cause air leakage and hinders their durability. By contrast, the ReISOs presented in this work are actuated with vacuum pressure and are resistant to pricking damage. This is because their inward collapse compresses the pinholes of the soft origami, thereby blocking the leakage of air (Figure 2M). The excellent damage resistance makes them especially suitable for applications in hazardous environments where pointed objects, such as nails or sharp stones, may pose a threat.

The ReISOs illustrated so far are centimeter-scale structures, limiting their applications in constrained spaces, such as the gastrointestinal tract, heart, and nasal cavity. However, recent developments in microscale fabrication and actuation⁴⁴ present an opportunity to downscale the intelligent soft actuators to microscale structures. As a soft sensor, the ReISO exhibits the ability to detect pressing or twisting stimuli. Nevertheless, the practical environment necessitates

Table 1. Capability comparison of our ReISOs with previous soft control devices

Capability	Soft valve ^{1,13-15,39,40}	Textile-based logic gate ⁴¹	Tube-balloon logic gate ^{42,43}	Buckling-sheet ring oscillator ¹²	This work
Actuation	–	–	–	✓	✓
Sensing	–	–	–	–	✓
Function multiplexing	–	–	–	✓	✓
Reconfigurable morphologies	–	–	–	–	✓
Plug-and-play	–	–	–	–	✓
Unified modules	–	–	–	✓	✓
Leak resistance	–	–	–	–	✓
Pressure type	Positive	Positive	Positive	Positive	Positive Vacuum
Low-cost, easy fabrication	–	✓	✓	✓	✓

the ReISO to be highly sensitive to obstacles. One potential way to improve sensing sensitivity is to use electrically driven soft actuation technologies, such as dielectric elastomer actuation,^{5,6} electrohydrodynamic actuation,^{45,46} and hydraulic electrostatic actuation,^{3,47,48} to construct soft modules coupling sensing, computation, and actuation. By harnessing such technologies, the contact of two conductive membranes could trigger the reversal of motion directions. In this work, we used a commercial pump and battery to drive the soft turtle, which decreases the compliance of soft robots. Nevertheless, these hard components, such as the pneumatic battery powered by chemical reactions, could be replaced with soft power devices in our future work.⁴⁹

MATERIALS AND METHODS

See the [supplemental information](#) for details.

DATA AND CODE AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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AUTHOR CONTRIBUTIONS

Z.J. and J.Z. conceived the idea and designed the experiments. Z.J., Z.H., Y.S., P.Z., W.T., and Y.Z. conducted the experimental work. Z.J. carried out the finite element simulation analysis, analyzed the data, and wrote the manuscript. J.Z. and H.Y. guided and supervised the whole project. Z.J., J.Z., K.X., F.L., and H.Y. revised the manuscript. All of the authors discussed the data and prepared the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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