Liquid Metal-Enabled Soft Logic Devices

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The controllable manipulation of gallium-based liquid metal (LM) droplet presents a promising option toward the goal of making fully soft machines, which features an autonomy via external administration apparatus. While most current endeavors mainly concentrate on LM-assisted actuations for soft robots, it is noteworthy that the peculiar behavior and LM droplet circuits thus enabled can be adopted as intelligent elements. Such characteristics will pave a way to innovate conventional logic devices and emancipate soft robots from the existing rigid machinery. Herein, LM-based soft logic systems are described which are capable of regulating soft machines on macroscale. The core element is a LM-based switch (LMS) with two specific types, both utilizing the LM droplet as a conducting medium. Soft logic gates of AND, OR, NOT, NAND, and NOR thus fabricated are demonstrated to generate electrical outputs as an integration of random inputs, and these signals can be adapted for electronic devices. For practical illustration, a logic accumulator is further constructed which can effectively regulate a pneumatic soft gripper within four states of inflation. The present LM-enabled logic devices are expected to offer a feasible strategy to manipulate future soft machines without the participation of traditional rigid controlling elements.

1. Introduction

The newly untethered soft robots exhibit a great potential of fully autonomous machines,[1,2] as many soft materials are capable of deforming to actuate the whole structures.[3–6] Furthermore, the motion can be ascribed to a sensing-and-feedback procedure of the device toward external stimulus,[7] so a simplification may arise for the control of soft robots in the future.

Although accessible in theory, what must be acknowledged is the deficiency of practical methods and devices for continuous control of soft robots. First of all, the effects of programming soft materials to realize movements varies a lot depending on the certain types, most of which can only achieve single predesign with low accuracy. Meanwhile, as the external stimulus for materials usually apply some traditional signals such as electricity,[4] heat,[3] fluid pressure,[6] and magnetism,[7] those related and widely used hardware like valve, pump, wire, and electronic module are still indispensable for signal transmission,[2,8] probably bringing damages to the soft components. The endeavor for more advanced smart materials is endless before the ultimate goal of flexible and accurate regulating, while to make these rigid devices more flexible is a practical and alternative choice at present, which will bring convenience to the control integration inside a soft structure. Recent achievements on soft valves have started the trial of eliminating rigid control devices in soft pneumatic actuators.[9] For example, an octopus-shaped robot could be accurately regulated to flail via a soft microfluidic oscillator embedded.[10] Another soft bistable valve was developed to help autonomous gripping when contacting the target, which, in a sense, has fulfilled a terminal sensing and feedback.[10] Although these early practices are still limited to simple modes like switching on-off, the expectation for integrating soft control devices into soft robots with multiple functions can be promising in the future.

The liquid metal (LM) generally refers to a series of pure metals or alloys, which feature low melting points around room temperature. Applications based on LMs have been vastly broadened, including advanced thermal management,[11] flexible electronics,[12] microfluidic or biomedical equipment,[13] and so on. In
a large extent to resemble the T-1000 robot in the classical science fiction movie *Terminator*, a group of recently fundamental findings on LM and its possible contribution to soft robots have been audaciously conceived. Overall, the fluidity of LM enables a soft conductivity and thus it can play a positive role for flexible circuits even intelligent droplet circuits in aqueous environment. Moreover, the electrochemically dynamic behavior of LM droplets, such as autonomous running and oscillation, has been applied to actuate lightweight elements (verified by some prototypes). While most attention is focused on strategies mentioned earlier, there still exists a possibility on soft control by LM. For example, the liquid-based switches (LMSs) have been applied in digital microfluidics, yet usually with demands for high voltages to obtain electrostatic effects. In contrast, the LM droplet can acquire electrically induced behavior with more moderate conditions, such as a transition with low voltages between bistable states (similar effects or applications were also reported in some earlier researches about mercury), like an on/off switch in logic gates. In this regard, the programmable LM-based physical variations as disclosed earlier may pave a way to a broader world of liquid-based controlling strategy. Such liquid-integrated system or droplet circuits can help build the intelligent system such as transistor, electrical switch, soft logic functional device even LM computer, which is essential for delicate manipulations of soft robots. However, a real functional soft logic system made of LM or the like is yet to achieve until now.

Herein, we demonstrate the feasibility on realizing soft controllers with a conceptually new design of LM-based logic gates, which is intrinsically different from those LM-based semiconductor devices in reports. The motion of LM under external electrical fields was first applied to design a liquid switch, where the transformation of droplet between two stationary states determined an on/off output of electrical signals. Subsequently, five soft logic gates: AND, OR, NOT, NAND, and NOR were built using the LMS of two types. This series of logic gates showed stable functionality for binary logic calculation and hence might become the cornerstone of more delicate logic integrations. Together with a soft trigger, we further combined a complete control module with a common pneumatic soft gripper, which acted as a logic accumulator to sum up different input pressures, thus enabling a four-degree control about inflation. In general, the softness of the whole device will ensure good compatibility, and the modular characteristics of LMS will be beneficial to sophisticated integration. In addition, the processing for electrical signals will also expand universality for more executors that have been used practically. This study represents a fundamental trial toward the ultimate goal of effective interaction between soft actuators and embedded soft controllers.

2. Results and Discussion

2.1. A Soft LMS

To fabricate the LM-based logic gates, a basic soft switch is introduced in advance, which makes the best of LM’s electrically induced motion (Figure 1). The switch consists of a cuboid channel with two pairs of inserted electrodes. The input group is defined as gate electrodes and placed parallelly near the bottom. Belonging to the output loop, a pin electrode and a pull electrode are set a little higher above gate electrodes. A droplet of LM, immersed in an alkaline solution, will switch between two steady states: keep contact with pin and pull electrodes or remain non-contact. The behavior of LM droplet will directly affect conducting of the output loop, thus generating an output voltage signal $U_{\text{out}}$. The gate electrodes are connected to a power source with input voltages $U_{\text{in}}$. According to the specific variation of LM droplet in an electrical field, either deformation or locomotion, two

![Figure 1. Patterns of D-type and L-type LMSs. a) The basic structure of a D-type LMS. b) The front view of a D-type LMS to exhibit the initial location of the LM droplet (“OFF” state). c) The basic structure of an L-type LMS. d) The front view of an L-type device to exhibit the initial location of the LM droplet (“ON” state).](image-url)
corresponding switching mechanisms are developed as in the following sections.

The first type is named as D-type LMS (Figure 1a). When no electrical signal is applied \( [U_{\text{in}} = 0 \text{V}] \), the LM droplet remains in its initial position, tethered by the pin electrode, and the output loop is unconnected (Figure 1b). The whole is defined as “OFF” state. Applying a voltage to gate electrodes will create an electrical field in the electrolyte solution, then inducing the droplet to deform because of the change of surface tension. At the same time, there always exists a chemical wetting between the pin electrode and the LM, which leads to a morphological stretching of the droplet and eventually connecting with the pull electrode. Consequently, the output loop will switch to be conductive and thus give an output signal \( U_{\text{out}} \). This state is defined as “ON” state. When the input is withdrawn, the droplet will return to its initial morphology and the switch will change back to “OFF”. Named as L-type LMS, the second kind of soft switch mainly applies the movement of LM droplet (Figure 1c).

Except the similarity of electrode pairs with D-type, this L-type has its unique design of the channel, referring to a 2.5% slope at the bottom. When there is no input voltage \( (U_{\text{in}} = 0) \), the droplet keeps still at the lowest of the channel due to gravity, thus constantly conducting the output loop and giving a \( U_{\text{out}} \) in an “ON” state (Figure 1d). When the input is on, however, the droplet will be induced to move toward the anode of gate electrodes, crawl along the slope and lose touch with pin and pull electrodes; therefore cut off the output loop and turn into “OFF”. In a nutshell, the D-type LMS is a normally off design while the L-type is a normally on one.

2.2. Electrical Conductivity and Interactive Response

The design of LMS is based on the on/off switching of output loop, which is directly affected by the interfacial contact between the actuated LM droplet and selected electrodes. Therefore, the response of LMs and the fastness between the two contacting components jointly determine the performance of LMS.

2.2.1. The Electrical Conduction

The electrically induced behavior of LM droplet is of primary focus. As is known to all, the commonly gallium-based LM features a high interfacial tension (about 624 mN m\(^{-1}\) for EGaIn\(^{[23]} \)) and highly probable oxidation, such that the interior of LM can remain stable and hence the transformation for droplet's shape must overcome the cohesion from high tension and the hindering from oxide layers. The study on such similar phenomena can be dated back to the Lippmann's Equation (Equation (1)), which described the charge density \( \sigma \) of the interface to the voltage relying of the interfacial tension \( \gamma \).

\[
\sigma = -\frac{d\gamma}{dU} \tag{1}
\]

Obviously, applying outer voltages electrolytical solutions can be an available method to adjust tensions. According to several existing studies,\(^{[24]} \) the LM can experience a large-scale deformation due to tension change when it contacts the anode in an alkaline solution. If not touching the electrode, the LM will move toward the anode. To be more specific, whether deforming or moving, the behavior of LM droplet is directly controlled by the applied voltage, thus becoming one key parameter for LMS.

As for the oxide layers on the LM droplet, the stickiness of surface oxides in air will lead to a tottering motion. Therefore, the usually applied acidic or alkaline solutions will also play a role to wipe off oxides. As for the concern about oxidations happening on electrodes, only contacts with the isolated anode will induce the oxidative growth, which will be intermittent (more details in the following part) and can hardly get accumulations, with few negative influences for the electrical behavior of LM.\(^{[26]} \)

Much finer results about the relationship between LM’s motion and inducing electrical field have been discussed in some previous researches. Herein, with a certain channel size and dosage of LM, a tunable voltage around 7 V can well meet the demands, which will be introduced in detail in the following section.

2.2.2. The Contact

The second issue centers on the interactive contact. For traditional solid switches, whether mechanically or electronically controlled, the action is finally based on a solid-to-solid contact, so the frictional loss is inevitable and hence bring challenges for durability of the device. While the solid-to-liquid contact in LMS can avoid this trouble, the actual connection, and stability, however, should be concerned. As mentioned earlier, with the sticky oxide layer wiped off in solutions, the large surface tension of LM will preserve the droplet as a close entity and thus hinder external intervention. Therefore, the contact must be ensured by some other measures rather than a mere touch. Considering that the LM droplet mainly operates in an electrolyte solution, we can try to use related surface reactions for a closer contact. The LM has been discovered to actively attach and react with several kinds of metals such as copper,\(^{[27]} \) nickel,\(^{[28]} \) and aluminum.\(^{[29]} \) The certain extent of reaction is mainly depending on the electrode potential of different substances, some of which may be too drastic to use up raw materials. In a nutshell, utilizing these reactions can be a reliable way to ensure stable interaction, but the material for electrodes must be cautiously selected to keep the reaction in a medium extent.

The function of two gate electrodes, no touch with LM droplet, is to generate electrical fields in solutions, so the inert silver material is used. As for the pin and pull electrodes, as the degrees of contact are discretely required in D-type and L-type, more candidates including platinum (Pt), titanium (Ti), molybdenum (Mo), tungsten (W), and copper (Cu) were selected to be tested, the choice of which combined stability, metallic activity, and preparation expenses together. An experiment was designed to measure the contacting degree (Figure 2a), which recorded the resisting effect on a needle-like sample among the whole cycle from plugging into LM to pulling out from it. It should be mentioned that the buoyancy was ignored because of the gap about several orders of magnitude, but actually it did exist (more details please find in Supporting Information). Results are shown in Figure 2b–f. Varying in a clockwise, the downward line in right side exhibits resistance for piercing the surface of LM, while the upward line in left side represents the beginning.
of pulling. The entering resistances all reach maximum at about 0.196 mN within a depth of 0.5 mm for all samples, but situations are different from each other during the pullout. Samples of Pt, Ti, and Mo behave similarly, where the resistance sharply declines to around zero at the start of pullout. As a consequence, these materials can satisfy the need of flexible detachment with the LM droplet. On the contrary, samples of W and Cu experience continuous impedances since the start with little decrease, and Cu even rushes to the peak at the very position of separation. This characteristics will undoubtedly ensure a more stable contact at the whole time. The entering resistance mainly results from high surface tensions of LM, so it keeps nearly constant in tests and can be overcome by electrically induced motion. As for the pulling difference above, it refers to physical or electrochemical effects between LM and other metals and the intensity of reaction. For example, the LM can corrode Cu after contacting and lead to the formation of an intermetallic layer of CuGa₂ on Cu plate surface. Such a layer will provide a stable metallic bond to improve the wetting behavior of LM on Cu surface in NaOH solutions, thus ensuring a stable contact.\(^\text{[27]}\) On the contrary, the extremely stable Pt and Ti may have few effects with LM, thus leading to a loose insertion.

**Figure 2.** Tests about the contact between solid electrode and LM. a) The schematic about measurements of the resisting effect in contact. b) The variation of resistance between Pt sample and LM during the overall process. c) The variation of resistance between Ti sample and LM during the overall process. d) The variation of resistance between Mo sample and LM during the overall process. e) The variation of resistance between W sample and LM during the overall process. The inset image shows a sunken interface when a peak resistance occurs during the entering. f) The variation of resistance between Cu sample and LM during the overall process. The inserted image depicts a convex interface when a peak adhesion force occurs during the separation.
Consequently, Cu was applied for pin electrode and W for pull electrode in the D-type LMS. The Cu featured a large adhesion with LM to hold a stable contact, whereas the W, sharing similarly strong adhesion with LM, could also separate away from LM more easily than Cu, ensuring a smooth separation. As for the L-type, both pin and pull electrodes were made of Pt because the LM droplet needed a relatively weak contact with electrodes and a flexible motion. In addition to the performance of the electrodes, the slope at the bottom in D-type could also partly help the contact at nonwork state. More details about specific crafts for to make electrodes are shown in Supporting Information (Figure 1 and 2).

As for the concern on losses about LM and electrode materials due to the contact, some more discussions are shown in the following sections. For the Cu electrode in the D-type LMS, this CuGa$_2$ layer would perform like a shelter to prevent more LM atoms from corroding Cu surface, thus avoiding more losses of both materials. In addition, in our moderate working environment, such a corrosion layer was very thin and would not bring serious damages to Cu electrode either. As for the W electrode, this metal would not wet LM to induce residues on its surface, or form alloys in such an solution,$^{[10]}$ and hence did not have losses itself. Moreover, the huge surface tension of LM, the small contact area (about 0.66 mm$^2$ supposing the insertion depth as 1 mm), and short contact time are all positive factors to reduce the loss (more experimental details in Supporting information).

For the L-type LMS, the Pt material universally features a strong chemical stability, so the influence of the metal losses can be ignored.

### 3. Performance and Applications

Based on mechanisms and experiments interpreted earlier, LMSs of D-type and L-type were fabricated and tested, respectively. Both two types were molded with polydimethylsiloxane (PDMS) and share the same channel size of 15 × 5 × 10 mm$^3$, with a dosage of 650 mg LM. Differences mainly lie on the material choice for pin and pull electrodes, details of which have been introduced earlier. Performances of D-type and L-type LMSs are presented in the following sections and related applications are discussed as well.

#### 3.1. The Switching between On and Off

The switching behavior was evaluated based on output signals in the output loop. To follow the convention in tests about electronic devices, we assigned the current in output loop $I_S$ as the resulting signal. Therefore, a constant direct current (DC) power of 3 V and a series resistor as a load were preinstalled in the loop.

The switch of LMS is a voltage-dependent process and controlled by the input voltage $U_{in}$. As shown in Figure 3a, the functioning status of D-type LMS can be approximately divided into three sections. When $U_{in}$ is set below 4.75 V, the electrical field to actuate LM droplet is not strong enough to compete against the anchoring from pin electrode. Therefore, the output loop maintains quite a weak conduction with 3 mA $I_S$ due to ionized electrolytes in the solution, and is virtually in an “OFF” state. As the applied $U_{in}$ increases to about 6.2 V, a sharp turn occurs where the electrical intensity reaches a threshold value to induce large deformation of LM, able to begin contact the pull electrode. Consequently, the conduction of output loop is largely improved with the participation of metals, and the $I_S$ zooms two orders of magnitude higher than the initial. At this point, the device has generated an “ON” switch. Therewith, a steady output will be obtained as long as the input $U_{in}$ is no lower than 6.2 V. It is worth mentioning that there exists a transitional area in range of 4.75–6.2 V for $U_{in}$, where $I_S$ experiences a fluctuation before the sharp turn. The reason lies in the deficient deformation of LM droplet in such voltages, which will cause vibration of droplet when it touches the pull electrode and attempts to overcome surface tension.

The function is inverse for L-type LMS. As shown in Figure 3b, when $U_{in}$ is low, the LM droplet will have a good contact with both pin and pull electrodes as preinstalled. The output loop is always “ON” with an $I_S$ near 250 mA. In such lower voltages, the induced movement of LM still cannot overcome the slope to climb away. As $U_{in}$ exceeds 5.1 V, the tendency of separation grows stronger and conductivity is disrupted. At the turning point of 6.5 V, the LM’s movement reaches an extent where separation comes about. The output loop is cut off with $I_S$ sharply decreasing to nearly zero. The device will keep “OFF” with even higher $U_{in}$. Similarly, the L-type also has a transitional area just above 5 V. Specific performances about D-type and L-type LMSs are shown in Movie S1 and S2, Supporting Information. As for the responsiveness, Movie S1 and S2, Supporting Information, actually exhibit the instantaneous agility in a single operation, where every varying about images at the top right corner of the frame means one trigger of input signals. In particular, the responding times acquired from the movie are about 0.07 s for D-type (0–6.99 V) and 0.08 s for L-type (0–6.89 V).

However, the performance under a discrete input cannot fully prove its reliability as switching devices are often required to frequently act, so further assessments should be fixed on the stability during continuous operations. The durability tests were conducted for both types. The input $U_{in}$ was reset as a series of square wave voltage of 7 V to ensure the switch, with frequency adjusted in the range of 0.5–6 Hz. As shown in Figure 3c, the output signals of D-type LMS can follow nimbly periodic variations at low frequency like 0.5 or 1 Hz. A hysteresis seems to emerge with a little higher frequency below 3 Hz while the device can still keep working normally. As the frequency exceeds 4 Hz, the mismatching begins to arise. The responsive time for trigger is still fast enough. However, the time for reset (the droplet needs to return to initial position for next use) cannot keep up with the increasing frequency. Therefore, the higher frequency leads to lags and switching curves become distorted, declaring a complete failure. In general, with a moderate working frequency not above 3 Hz, motions of LM droplet can harmonically follow the variation of input $U_{in}$, and the LMS remains good operation. Compared with traditional rigid switches, such an adaptability is not inferior.

If taken into further discussion, the following quality of LMS toward high frequency relies both on the response time and the reset time. The response time now is quite fast, and improvement for response time will lie on strengthening the alkalinity or the actuating voltage, which nevertheless will bring some unstable problems (referred in the following part), and hence is unnecessary. Therefore, more efforts should be made to
Figure 3. The operation and output of the LMS. a) Performances of the D-type LMS: (1) The initial spherical morphology of the LM droplet with no input voltage at the OFF state; (2) The elongation of the LM droplet to contact pull electrode with an input voltage above 6.2 V and a following ON state; (3) The curve about output current $I_s$ varying with the increase of input voltage $U_{in}$. b) Performances of the L-type LMS: (1) The LM droplet initially keeps contact with both pin and pull electrodes and holds an ON state; (2) The locomotion of LM droplet leads to a break off between pin and pull electrodes and an OFF state consequently; (3) The curve about output current $I_s$ varying with the increase of input voltage $U_{in}$. c) The responses toward input voltage with different frequencies ($f = 0.5, 1, 2, 3$, 4, 5 Hz) of the D-type LMS. d) The output performances of LMSs during a durability test with 400 cycles: (1) D-type; (2) L-type.
improve the reset process, specifically the reset motion of LM droplets. As this process is dependent on spontaneous motion of droplets without electrical induction, practical methods can include shortening sizes of the channel to decrease the total moving distance, reducing the amount of LM for less resistance in the solution, and slightly lowering the insert depth of the electrode in the LM droplet for more rapid separation. Meanwhile, the normal function of LMS should be ensured as the essential precondition. For example, a too small bulk of LM will increase the contacting instability with electrodes. In general, the LMS of this design is subject to the category where the switching function is based on mechanical behavior in macroscale, so inherently it may not be suitable for occasions with high-frequency demands. The LMS has its own perfect stage at a moderate working frequency with satisfying performances. Last but not least, if in the future the LMS does have to face high-frequency demands, current applied mechanism must be radically altered. In our recent experiments, we managed to fulfill a high-frequency vibration of LM droplet in macroscale in a similar environment. It still needs more researches, but such continuous endeavors can pave a way toward this goal.

As for the stability regulations from other aspects, a test on the life of both types of LMSs was conducted. Results shown in Figure 3 demonstrate the stability and robustness, which are also indirect responses to the concern about metal losses discussed in Section 2.2.2. In addition, a bending test was also conducted to prove its basic adaptability to mechanical deformation (Note 4 and Figure S6, Supporting Information). At the end of this section, Table 1 is additionally compiled to summarize the basic performance parameters introduced earlier about both two kinds of LMSs.

### 3.2. Soft Logic Gates based on LMSs

The steady performances of LMS let us try to build logic devices as the cornerstone for ultimate soft control entities. The basic configurations of our logic gates are shown in Figure 4. The whole loop obtains a constant power supply of 3 V and a protective resistor. The control module is connected inside and can be changed easily for different targets. The actuation for LMS is relied on an independent power supply with a voltage of 7 V to ensure infallible switches. Herein, we assigned the voltage across the control module \( U_{\text{out}} \) as an output signal for the convenience in subsequent applications. In our pre-experiments, the obtained voltage \( U_{\text{out}} \) generally fell in the range of 2.4–2.6 V after the whole loop was steadily conducted, the fluctuation chiefly resulting from electrolyzation of solutions and measuring errors. Therefore, following the convention in digital logic gates, we defined \( U_{\text{out}} = 0 \) as the binary value “0” while \( U_{\text{out}} = 2.4–2.6 \) V as the binary value “1”. As for input signals, importing 7 V voltages was assigned the binary “1” and importing no voltages the binary “0”. In addition, A represented the input value (using subscripts for more than one if needed) and B indicated the output value.

#### 3.2.1. AND

An AND gate multiplies its inner two serial input signals to generate an output value. There are four assemblies in the truth table for an AND gate. We used two D-type LMSs, with their own power sources, to build this logic gate (Figure 4a). The output \( U_{\text{out}} \) and binary values were measured and recorded as a function of input A. As curves shown, values of \( A_1 \) and \( A_2 \) experienced periodic transformations between 0 and 1 due to the square-wave power supply. In this configuration, only when \( A_1 = 1 \) and \( A_2 = 1 \) (thus connecting both two breaking points) will the whole loop be conducted, thus exporting a value of \( B = 1 \). The four situations in the truth table can be correspondingly found in the graphic, especially showing an agility in section with \( B = 1 \). The deviation in several sections (with input of 00, 01, and 10) resulted from the reality varying from ideal device. More specifically, the resistance of an ideal electrical switch should be near infinity when not on, but in fact, the ionization in strong alkali solutions and the electrolysis of solvents would bring about quite small leak current.

#### Table 1. A summary of the basic performance parameters of the LMS.

| Characteristic       | D-type      | L-type      |
|----------------------|-------------|-------------|
| Basic size           | 15 × 5 × 10 mm³ | 15 × 5 × 10 mm³ |
| Electrode            |             |             |
| Pull                 | Cu wire     | Pt wire     |
| Gate                 | W wire      | Pt wire     |
| OFF                  |             |             |
| Voltage \( (U_{\text{on}}) \) | 0–4.75 V   | >6.5 V      |
| Current \( (I_{\text{on}}) \) | <4 mA      | <5 mA      |
| Switch               |             |             |
| Voltage \( (U_{\text{off}}) \) | 4.75–6.2 V | 5.1–6.5 V  |
| Current \( (I_{\text{off}}) \) | –          | –          |
| ON                   |             |             |
| Voltage \( (U_{\text{on}}) \) | >6.2 V     | 0–5.1 V    |
| Current \( (I_{\text{on}}) \) | Around 250 mA | Around 250 mA |
| Response time (single operation) | 0.07 s     | 0.08 s     |
| Adaptable working frequency | ≤3 Hz       | ≤2.5 Hz     |
| Life span            | ≥400 cycles | ≥400 cycles |
| Bending tolerance (Δy) | ≤3 mm     | ≤5 mm      |
Meanwhile, the series connection features a strongly mutual influence on voltage distribution among different appliances. Generally, the disturbance was quite limited and would not influence the output value \( B \). The disturbance can be diminished by decreasing the concentration of electrolytes to maintain the conductivity of solutions in a lower level.

Figure 4. Soft logic gates based on the LMS. a) AND: (1) The symbolic depiction and the truth table; (2) The schematic of circuit with two binary inputs and one binary output; (3) The testing curves of four possible states by varying the two inputs independently. b) OR: (1) The symbolic depiction and the truth table; (2) The schematic of circuit with two binary inputs and one binary output; (3) The testing curves of four possible states by varying the two inputs independently. c) NOT: (1) The symbolic depiction and the truth table; (2) The schematic of circuit with one binary input and one binary output; (3) The testing curves of two possible states by varying the one input. d) NAND: (1) The symbolic depiction and the truth table; (2) The schematic of circuit with two binary inputs and one binary output; (3) The testing curves of four possible states by varying the two inputs independently. e) NOR: (1) The symbolic depiction and the truth table; (2) The schematic of circuit with two binary inputs and one binary output; (3) The testing curves of four possible states by varying the two inputs independently.
3.2.2. OR

An OR gate will output the sum value of two binary inputs, and also has four cases in the truth table. This function can be achieved by parallely laying two D-type LMSs in the control module. The set of \( A_1 \) and \( A_2 \) was similar to that described earlier. When any one of input gave 1, the whole loop would be conducted and export a stable \( U_{out} \). Curves in Figure 4b show all the four kinds of variations with excellent responsiveness. As mentioned earlier, the nonidealized switching of a single LMS was accompanied by variations of the resistance, which would bring direct impacts on the voltage distribution of each device in a circuit with series arrangement. However, the parallel connection of two LMSs could effectively decline such interferences due to mutually independent branches, so the operation could be quite smooth and stable.

3.2.3. NOT

A NOT gate will reverse its original input value, with a simple truth table of two cases. Considering the characteristic of D-type, we can easily fulfill this logic gate with just one single LMS. As shown by the curves (Figure 4c), an input \( A = 1 \) would generate a circuit break of \( B = 0 \), and vice versa. The agility was excellent as well.

3.2.4. NAND

A NAND gate is a superposition of an AND gate and a NOT gate with multiple inputs and one output. As there are four cases in the truth table, so two switches are required. In this configuration, we used two L-type LMSs parallel in the whole loop with their own power supplies (Figure 4d). When \( A_1 \) and \( A_2 \) were 1, both two branches were cut off and thus there would be no output voltage with \( B = 0 \). The loop would be conducted as long as at least one branch was connected, with a binary value 0.

3.2.5. NOR

Typically, a NOR gate cascades an OR gate and then a NOT gate with multiple inputs and one output. To simplify the configuration and ensure stability, here we used two series L-type LMSs to achieve all the four cases in the truth table (Figure 4e). The whole loop would keep off with \( B = 0 \) as long as there existed disconnections, which means that there was one input binary value 1 or more. Only when both \( A_1 = A_2 = 0 \) could the output be \( B = 1 \).

3.3. A Soft Four-Degree Logic Accumulator Based on LMSs

To further explore the possibility of LMS-based devices as a soft controller to manipulate other soft actuators, we applied two D-type LMSs to construct an equivalently logic accumulator and regulated actions of a soft gripper, which could be transformed among four levels of pneumatic inflation. At first, we utilized a soft trigger to turn on/off the control module, aiming to improve its integrity. The soft trigger was composed of a silicone-made cylinder with a built-in channel and a pair of electrodes at both ends. A certain bulk of LM, immersed in alkaline solutions, was initially enclosed in the pit of the channel. When in its rest status, the trigger was disconnected. If a stress was put right above the pit on the surface by a user, the LM would spread from the cave because of the shearing effect of fluids via squeezing. The metal flow along the channel would then rise and get in touch with both electrodes and connect the element. Therefore, the trigger would be on to ensure power supply for the control module (Figure S3, Supporting Information).

The soft gripper obtained two branch intake pipes (\( T_1 \) and \( T_2 \)) to directly impact the extent of inflation with different incoming pressures (\( T_1 = 6 \) kPa, \( T_2 = 3 \) kPa, gauge pressure relative to 1 atm atmospheric pressure). The status of inner pressure of the gripper was defined as \( P_G \). The switch of intake pipes was dependent on two solenoid valves separately. The configuration of the control module is shown in Figure 5a,b. The accumulator comprised two D-type LMSs, each with one soft trigger linked and then connected to one solenoid valve. The power source supplying the accumulator was set in 7 V. When the soft trigger was pressed on, the D-type LMS would be switched on, and thus activate the solenoid valve to let gas in. The whole status could be assigned binary value \( T = 1 \). On the contrary, if the soft trigger was not pressed to be connected, the LMS kept off and the valve would not be opened without pneumatic input, this status assigned \( T = 0 \). Such regulations on the two intake pipes would bring about differences of importing pressures, and hence lead to inflation of the gripper in several extents. As shown in Figure 5c,d, two mutually independent inputs generated \( 2^{2} = 4 \) types of results about bending of the gripper. In addition, these four acting states clearly reflected the performance of such a dual-channel accumulator, which could memorize intermediate results about input pressures and conduct superposition. For example, when the dual inputs were changed from \( T_1 = 0 \) and \( T_2 = 1 \) to \( T_1 = 1 \) and \( T_2 = 1 \), the degree of inflation was reinforced because of the addition of \( T_1 \) channel and the maintaining of on-state about \( T_2 \) channel. Those binary 00 troughs in curves of Figure 5c are specially reset by us to divide these four states more clearly for observation, whereas the variation could be continuously conducted in practice with no need of reset (Movie S3, Supporting Information).

As a proof of concept, this soft logic-assisted gripper is a preliminary prototype for more delicate soft control entities in the future. The holistic softness will ensure harmonious insertion and friendly interaction with humans. More diverse combinations of basic soft logic gates will enable more elaborate manipulations. These devices will acquire the ultimate versatility for more kinds of soft actuators and eventually the soft robot.

4. Conclusion

In recent years, human’s fascination for soft intelligent devices has been growing more and more passionate, for its potentials in friendly interaction, versatility, and mechanical robustness. However, since the deformation-based behavior of a soft device is quite different from those under the guidance of rigid-body kinematics, an effective and convenient control for the soft entity is remaining a major challenge. In terms of ever-emerging endeavors, the strategy to develop smart soft materials that can be preprogrammed and even erased/reprogrammed for
elaborate control is quite laudable and promising. Nonetheless, the development for new types is not quite easy work, while those widely tried soft materials like silicone can still not serve well as smart as expected. Alternatively, applying analog or digital control paradigms into soft structures may take advantage of numerous existing methods and loosen the demand for materials, but rigid components or electronics are probably not compatible with soft systems in most occasions, thus obstacles kept lying in available soft devices such as logic gates, digital analog converter, and so on.

As an alternative, this article explores the feasibility of soft logic gates, which is based on the macroscopic behavior of LM droplets. A LMS was primarily designed to build the liquid-involved logic gates, which could be divided into the normally off D-type and the normally on L-type. The electrically induced deformation or locomotion of LM enabled the droplet to transform between fixed electrodes, hence conducting or closing the loop and exporting corresponding signals. The spatial scale of LM involved motion was quite small without bulky ancillary equipment, thus easier for miniaturization and integration. As the switch featured processing for electrical signals, it could possibly be able to regulate more kinds of end-executors as long as they are electrically related. In addition, such a LM-based logic devices demonstrates the potential that macroscopic variations of liquid can be designed as processors for reception, conversion, and exportation of electrical signals. Due to the natural harmony with soft structures, they may hold a promise for the ultimate autonomy and control of soft robots in the near future.

5. Experimental Section

Fabrication of the LMS: Preparation of the LMS began with molding of soft channel to hold the LM droplet and alkaline solutions, which was made of PDMS (Sylgard 184, Dow Corning, USA). The size of this channel was 15 mm x 2 mm x 10 mm with a wall thickness of 8 mm. An aluminum-made mound was applied for the curing of PDMS at 75 °C for 2 h. For the convenience of filling liquids later, the top roof was separately made rather than integration. Then, holes (d = 0.3 mm) to insert electrodes were made via carefully drilling on the soft walls, the installing positions of which varied with the specific type of LMS as mentioned earlier. The fixing of thin electrodes was mainly based on the interference fit along with the elastic compression from walls. More details about the fabrication of electrodes are introduced in Supporting Information. Next was the injection of liquids. The E-Gain (74.5% Ga and 24.5% In in a mass ratio) with a dosage of 650 mg was placed at its initial site, contacting the pin electrode for D-type or both pin and pull electrodes for L-type. The NaOH solution
(0.5 mol L\(^{-1}\)) was poured in until its level reached edges of the channel. Finally, a tiny uncured layer of PDMS was smeared at the interface between the top roof and the whole structure, whose solidification would adhere them together.

**Measurements about the Resistance from Solid-to-Liquid Contacts:** The contact resistances between the LM droplet and electrodes with different materials were tested via a surface tensiometer (DCAT21, Dataphysics Co., Ltd., Germany). Before measurements, a bulk of E-Gain was completely immersed in a NaOH solution for preventing surface oxide layers, all liquids placed in a glass dish on an object stage. Note that the moving component was LM in the dish rather the needle-like sample, and the detection speed, insertion speed and escape speed of the object stage were all set at 0.15 mm s\(^{-1}\). In addition, the top end of sample was initially set in the solution with a distance of 1 mm away from the surface of LM. As the object stage rose to get in touch with the sample, the sample would receive an upward force, which was equivalent to that resisting effect and was defined as a negative value. After the sample pierced the LM, the stage would continue rising another 2 mm and then turned to drop until they were completely separated from each other. Furthermore, the downward resisting forces during the separation were positive values. To more clearly show the differences of contact and separation among several kinds of samples, an optical module of the contact angle meter (JC2000D3, POWERREACH Co., Ltd., China) was in addition used to record the changing patterns at the LM interface during insertion and separation.

**Testing for the Performance of Logic Gates:** The switching performance of LMS was characterized by a data acquisition instrument (Agilent 34970, Keysight Technologies, USA) and a DC power supply (USB30, Keysight Technologies, USA). This multichannel DC power served two pairs of electrodes in the LMS and the output loop. The probes from two independent channels of Agilent 34970 were parallelly connected to gate electrodes and a standard resistor (10 \(\Omega\)) in the controlled circuit respectively, aiming to collect voltage signals. During the experiment, the input signal \(U_{\text{in}}\) on the gate electrodes was regulated manually, while the voltage between pin and pull electrodes remained constant. Current signals \(I_s\) from the output loop were calculated based on the voltage values of the resistor from Agilent 34970. As for tests on the frequency response of LMS, a signal generator (FG3051C, Tektronix Inc., USA) was applied to generate input signals with variable frequencies, connecting with gate electrodes of LMS. At the same time, the acquisition for output voltages was changed to an oscilloscope (MSO2014, Tektronix Inc., USA), replacing the former channel of Agilent 34970 for higher precision. The configuration for performing tests of logic gates is similar to that about LMS introduced above. Each LMS in the system had its own channel as inputs in the same DC power. The outputs of logic gates were measured as voltages on a new pull-up or pull-down resistor, with the assistance of Agilent 34970.

**Application of the LMS-based Logic Accumulator:** The pneumatic soft gripper was fabricated by a subsection casting due to its hierarchical structure for anisotropic expansion. The gripper mold was made of high-performance nylon resin via a 3D printing manufacturing. Then the molding process was conducted in three steps. The first layer of soft chambers was cast with highly stretchable silicone (Ecoflex 00-30, Smooth-On, Inc., USA). Then came the second step using high-density spray melting non-woven fabric as the nonstretchable layer. Curing of the first layer would help fix the fabric, which was conducted at 65 °C for 30 min. Finally, the third layer of silicone Ecoflex 00-30 was poured over the fabric, and completed the casting after it solidified. The cured gripper was demolded and tubing was placed into the gripper at the middle position of the side wall. The soft trigger was casted by PDMS (Figure S3, Supporting Information). A small double-head air pump (ZRS102PM, Zhizhen Technology, China) was then attached to the tubing as sources, which could provide two different levels of in-take pressures. For the control unit, each of D-type LMSs in the logic accumulator was connected with an electromagnetic valve in one branch tube. The same DC power supply (USB30, Keysight Technologies, USA) served both the pump and the logic accumulator. A digital high-precision pressure sensor (TY-YBS-100, Huai’an Instruments, China) was used to measure the pressure variation inside the gripper. In addition, the Agilent 34970 was also used for data acquisition. As for the inflation of the soft gripper, it was recorded by a digital camera (Canon 70D, Canon, Inc., Japan).

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

**Acknowledgements**

D.-D.L. and T.-Y.L contributed equally to this work and should be considered to be the first coauthors. This work was partially supported by NSFC under Grants Nos. 81701850, 91748206, and 51890839, and the Frontier Project of the Chinese Academy of Sciences.

**Conflict of Interest**

The authors declare no conflict of interest.

**Data Availability Statement**

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

**Keywords**

droplet circuits, electrically induced switches, intelligent elements, liquid metals, soft logic systems

Received: October 29, 2020
Revised: December 23, 2020
Published online: March 18, 2021

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