Programmable Liquid Matter: 2D Shape Deformation of Highly Conductive Liquid Metals in a Dynamic Electric Field

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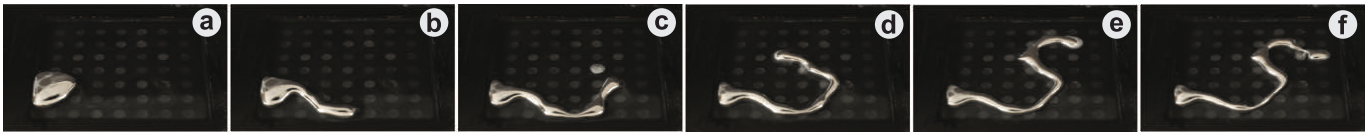

Figure 1. Programmable liquid matter making nonlinear shape of alphabet "S". 7x7 electrodes array dynamic switching to control EGaIn to make an 'S' shape.

ABSTRACT

In this paper, we demonstrate a method for the dynamic 2D transformation of liquid matter and present unique organic animations based on spatio-temporally controlled electric fields. In particular, we deploy a droplet of liquid metal (Gallium indium eutectic alloy) in a 7x7 electrode array prototype system, featuring an integrated image tracking system and a simple GUI. Exploiting the strong dependance of EGaIn's surface tension on external electric voltages, we control multiple electrodes dynamically to manipulate the liquid metal into a fine-grained desired shape. Taking advantage of the high conductivity of liquid metals, we introduce a shape changing, reconfigurable smart circuit as an example of unique applications. We discuss system constraints and the overarching challenge of controlling liquid metals in the presence of phenomena such as splitting, self-electrode interference and finger instabilities. Finally, we reflect on the broader vision of this project and discuss our work in the context of the wider scope of programmable materials.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

Author Keywords

Liquid metal; Programmable Matter; Gallium; Blob Animation; Electric Field; Marangoni Effect; Shape Changing Display; Reconfigurable Circuit; Smart Material.

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INTRODUCTION

The concept of "programmable matter" is a long-term aspiration for many researchers in the robotic and display domains [37, 8, 15]. This vision comprises the possibility of programmatically controlling physical objects, allowing them to change their visual appearance, physical shape and provide on-demand functionality, both replicating and surpassing the functionality of current digital displays.

As described below (in the Background section), many different solutions have been attempted towards programmable interfaces. On their quest towards precisely controllable deformations, researchers looked first at naturally deformable materials (e.g., fabric, rubber, gels) and then at interactive arrays of suspended objects actuated across the display (e.g., levitated polystyrene balls). This prior work shows a trend of moving ever closer towards using a liquid display (i.e., where molecules move along parrallel planes). Thus far, however, this vision has not been realised.

In this paper, we explore the concept of programmable *l*iquid materials: a class of materials where the deformability is intrinsic in their molecular structure and/or their physical state. Liquid metals are an extremely promising class of materials for deformable applications: their unique properties — such as voltage controlled surface tension, high liquid-state conductivity and liquid-solid phase transition at room temperature — open new possibilities in soft robotics and shape changing displays. Finally, once a certain quantity of liquid metal (i.e., a "blob" in the following) is deployed, features like self-locomotion, self-rotation and deformation, as well as stiffness and density modulation, are easily achievable.

As the first step to explore programmable liquid matter, we present the following works as our contributions:

- A hardware framework to control liquid metal blobs to create non-linear curved line patterns.

- A GUI to enable users to interactively and physically render the complex liquid shape with a 49-electrode array control system (Figure 1).
- Demonstration of reconfigurable circuit application based on programmable liquid metal enabled by our approach.

BACKGROUND

Actuated Material Interfaces

Much previous work has explored shape-changing solutions for interactive surfaces and devices. Many natural materials, including gel [24], soap bubbles [5], ferrofluids [42, 43] and magnets [22] have been used to create programmable surfaces and shapes. Other programmable surfaces used, for example, fabric [34], rubber [10] or pins [6, 32].

One of the most common methods of providing feedback is to actuate with pin-like rods through mechanical actuation [6] to form constraints or to create widgets [32]. In another established approach, a deformable interface is achieved by moving objects in 3D space, like a levitated ball [19] or polystyrene beads [35]. In contrast to work which actuates individualised fixed objects, many have focused on manipulating materials themselves to create shape-change. Coelho and Zigelbaum, for instance, explore shape memory alloys (SMAs) to facilitate shape change. SMAs can be treated to acquire a given shape, which the material remembers indefinitely, and can return to it when heated [2].

Driven by scientific advances, more and more materials are being incorporated into shape changing interfaces with the hope of providing physicalised, mutable, visio-tactile feedback. Such interfaces are driven by pneumatics [9], magnetic forces [27] and high voltage [35], to name a few. Roudaut et al. [33] note how each material sits on a continuum in terms of the actuation it can achieve and the strength of its deformation, among a number of factors which affect the potential deformation of a material.

Fluids for Actuated Interfaces

Fluids are ideal candidates for shape-changing interfaces, as they are highly flexible and can therefore be affected in a number of ways. Prior fluid-based interfaces have been mostly designed for artistic displays to visualize binary patterns with physical pixels. For instance, Tsujimoto et al. deployed reversible water condensation using peltier devices in a grid to show a letter of the alphabet and number interactively [40]. Parkes et al. used wet felt to show patterns using water condensation [31]. Hirayama et al. controlled soap bubbles in a matrix to show different patterns [12]. UK artists Heather Ackroyd and Dan Harvey created an algae display in a slowly changing liquid pixel grid [30] and Masson et al. manipulated ferrofluid bubbles to create notification patterns [23].

Fluids can be used within a material to actuate it, like, for instance, Harrison and Hudson's dynamically shape changing buttons [9], which inflate predetermined areas on a screen to form a tactile interface. Likewise, fluids have been used to provide a sense of variable haptic feedback, for example, Jansen et al. used magnetorheological fluid to control the texture of a display dynamically [16].

Furthermore, the possibility of affecting surface tension (i.e., the force maintaining an interface) with some external stimuli (e.g., thermal, electrical, magnetic) has attracted both researchers and artists, leading to unique physical animations in response to external forces. Kojima et al. controlled motion of water droplets on a hydrophobic fabric deformed by a grid array of linear actuators [17] and presented blob locomotion. Wakita et al. proposed interactive displays to animate ferromagnetic blobs with magnetic field such as splitting and coalescence [43, 42]. These works, however, do not exhibit the rich state-changing capabilities needed to create a scalable and complex 2D shape due to the limited range of variability of the surface tension inherited to the used fluids.

Liquid metals, on the contrary, can dramatically reduce the surface tension in response to an applied electrical voltage and can deform their shape with a higher level of freedom.

Liquid Metal Control

In 1875, Lippmann first noted the electrocapillary action that modulates the surface tension of a liquid metal blob (in his case mercury, Hg) immersed in a surrounding electrolyte. He elicited movement of the blob by controlling a small amount of voltage across the interface (see [1]).

As an alternative to Hg, the alloys of the low toxic and high conductive Gallium (Ga) — such as Galistan (an alloy of Ga,In,Sn) and EGaIn (alloy of Ga, In) — have attracted many researchers to investigate a variety of electrocapillary applications in optical switches [39], microfluidic circuits [29], flexible printed electronics [45] and 3D printing [39]. Crucially, a blob of one of these alloys, placed in an alkaline or acidic solution, would exhibit large transformations in surface tension when a voltage is applied, resulting in locomotion of the alloy.

Yao et al. [46] show the locomotive characteristics of a blob of EGaIn travelling through gaps five times thinner than its own original size and quickly returning to its original state, exhibiting what they describe as "worm-like locomotion". Further, Zhang et al. [47] describe how the effect of amalgamating gallium and aluminium can be used to autonomously propel blobs, guided by magnetic or electrical fields.

Liquid Metal Interfaces

Recent work has begun harnessing the unique properties of liquid metals to create dynamic tangible user interfaces. Niiyama et al. [26], for instance, used liquid metal to alter the shape of and affect the weight of a device by pumping Ga-In-Tin eutectic with a bi-directional pump. Further to this, Lu et al. utilised liquid metal as a means of creating widgets to produce visual effects and tactile displays [21]. They chose EGaIn, which has a spherical shape when at rest, and becomes a flat, film-like material when a voltage is applied. This process is reversible, so is particularly useful for providing both physical feedback and visual effects for actions such as hidden/revealed or checked/unchecked, as demonstrated by the authors. Likewise, these authors achieved dynamic haptic feedback when the voltage was applied and removed, making the sphere and

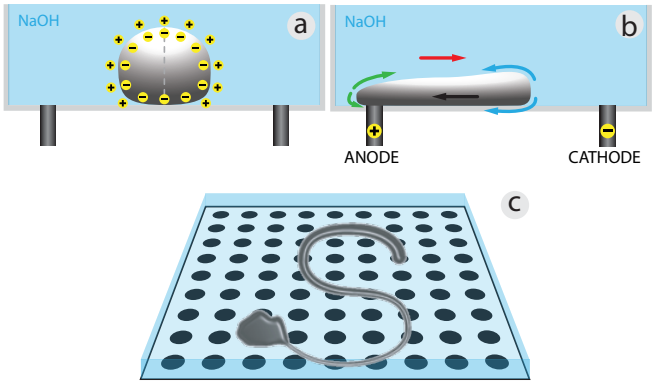

Figure 2. How the electric field creates deformation (a) A liquid metal blob far from the electrodes and in absence of field is subject to no force (b) Deformation occurs when the blob is in contact with one of the electrodes and an electric voltage is applied across it. (c) Deformation in this work as a 2D process.

film shape of the liquid metal. Their methods, however, constrained the actuation of EGaIn to channels, thus restricting the interface to a non-mutable, general purpose display.

In this paper, we go beyond these limitations and propose a method for the full manipulation of liquid metals, using electrode arrays to create dynamic patterns in an open-channel set-up. This is a step forward, which opens many opportunities for creating novel exciting visio-tactile experiences, especially when liquid metals such as EGaIn are the state-changing materials.

PROGRAMMABLE LIQUID MATTER

The most generally accepted expression for the (di-)electrophoretic (DEP) force acting on a fluid in an electric field is [18]:

$$\mathbf{F}_{\mathrm{e}} = q_{\mathrm{F}}\boldsymbol{\nabla}\Phi - \frac{1}{2}E^2\boldsymbol{\nabla}\varepsilon + \frac{1}{2}\boldsymbol{\nabla}\left[E^2\rho\left(\frac{\partial\varepsilon}{\partial\rho}\right)_{\mathrm{T}}\right] \quad (1)$$

where $E = \nabla\Phi$ is the electric field intensity, ε the electrical permittivity of the medium and q_{F} the free charge density. Only the first term in eq. (1) depends on the sign of the electric field (Coulomb force): it is present when free charge build up occurs and, in such cases, it generally predominates over the other electrical forces. The other two terms, of dielectric origin, depend on the magnitude of E^2 and are therefore independent of the field polarity. In particular, the second term in eq. (1) is due to non-homogeneities of the dielectric constant: acts perpendicularly to interfaces, like an electrostatic pressure, causing Marangoni-like instabilities [41] and changes of shape. The third term in eq. (1) is caused by non-uniformities in the electric field distribution: in the presence of interfaces acts like a body-force, e.g., moving bubbles in reduced gravity [28].

A liquid metal blob in an electrolyte solution is highly conductive ($\varepsilon \ll 1$) and highly reactive (i.e., with the electrolyte) at the same time. When the blob is not in contact with any of the electrodes, and there is no voltage applied anywhere, the charges in the electrolyte induce a uniform charge distribution on the blob's surface, as shown in Fig. 2(a). In this case, no external force is applied to the blob.

However, when the blob is in contact with one of the electrodes – e.g., the anode in Fig. 2(b) — and a suitable voltage is applied to one or more of the other electrodes, the charge distribution in the blob gets altered due to the difference in the conductivity between the electrolyte and the liquid metal. As a result, charge build-up occurs at the blob's interface, an electric double-layer (EDL) is formed and each section of the interface is subject to a Coulomb-type force that causes deformation in the direction of the electric field, as shown in Fig. 2(b). Starting with the pioneering work of Beni et al. [7], this phenomenon, under the name of continuous electrowetting (CEW), has been used by many authors to induce 1D motion in confined channels, bounded by conductive walls.

In this work, we explore a different situation: our liquid metal blobs are free to move in a 2D plane and are confined only by the display surface with the electrodes (at the bottom) and by the elecrolyte-air interface on top. Specifically, our goal is to maintain connectivity of liquid metal with the anode, using a set of pre-distributed voltages on one or more of the other electrodes to force the liquid metal into the desired complex shapes, as shown in Fig. 2(c). To our best knowledge, there are no other computational approaches that achieve such full maneuverability for liquid metals in 2D.

We explain our observations looking directly to the local value of the liquid-electrolyte surface tension $\gamma_{LE}(x, y)$, where x and y are the coordinates of a specific part of the interface in the 2D plane. Since Lipmann's pioneering work[20], many experiments have, in fact, confirmed that local surface tension can vary by $\approx 50\%$, even with a potential difference of less than 1V across the interface. The governing law is

$$\gamma_{LE}(V, x, y) = \gamma_{LE}(0) - \frac{1}{2}C \cdot [V(x, y) - V(0, 0)]^2 \quad (2)$$

where $\gamma_{LE}(0)$ is the maximum value of the surface tension, $V(x, y)$ is the local voltage drop between the interface in position (x, y) and the anode – in position $(0, 0)$ – C is the EDL's capacitance per unit area (assumed to be constant in the first instance, but in reality is also dependent on the local electric potential $V(x, y)$). Eq. 2 means that the higher the applied voltage, the less the surface tension becomes on the side of the blob facing the lower voltage (i.e., the cathode). The liquid then "attempts to wet more" the areas of lower surface tension, as they are energetically more favourable: like in a Marangoni effect [41], the liquid metal readily deforms from its spherical shape and flattens on the surface, reaching towards the cathode.

In this context, most of the movement is experienced by the points with the highest voltage (compared to the anode). Not only does applying a voltage to a specific electrode create an electric field that rapidly decreases with distance from the cathode, but the parts of the interface parallel to the lines of the field experience very little force.

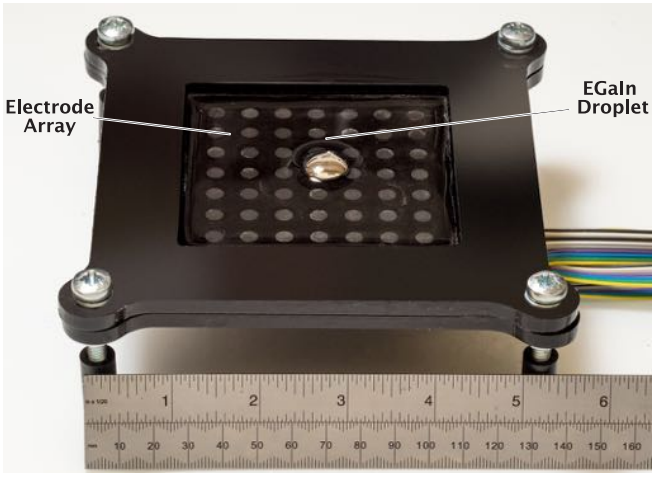

Figure 3. The 7x7 graphite electrode array display used in this study (top view). The figure also highlights the size of the EGaIn blob using during the experiments (9 grams).

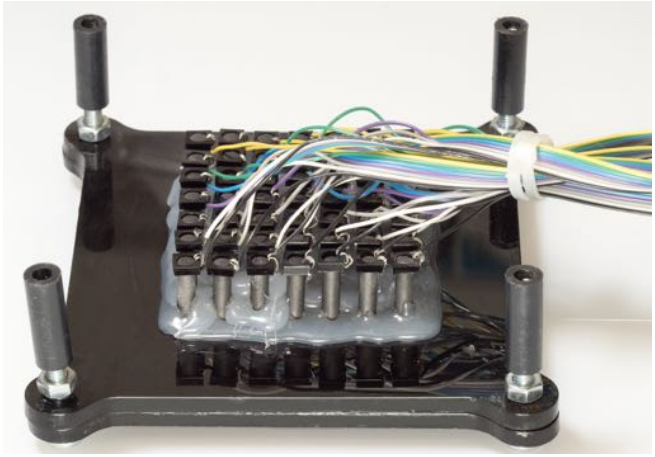

Figure 4. Back side view of 7x7 graphite electrode array display. Sealing between the graphite electrode rods and the acrylic substrate of the display is achieved through a silicone glue, which is NaOH-resistant. Each graphite rod is wired individually through a laser-cut acrylic adapter. The height and balance of the display table level is adjustable with respect to the ground by rotating the screws of the four supporting legs.

PROTOTYPE SYSTEM FOR LIQUID METAL CONTROL

In this section, we describe the proof-of-concept set-up where we exploit the surface tension reduction (described above) to program deformation into a given liquid metal blob. We detail the hardware design (i.e., a display made of a 7x7 electrode array), the GUI-based control system and finally the feedback system (i.e., an augmented camera).

Liquid Metal

In this study we use a liquid-metal alloy called EGaIn (eutectic gallium indium: 75.5 wt.% Ga 24.5 wt.% In) [4, 25] immersed in a 1M solution of NaOH. EGaIn is twice as viscous as water (1.99×10^{-3} Pa $\cdot$ s, has a high conductivity ($\sim 3.4\times10^{6}$ S/m) and is a stable liquid above 15.5 ^{o}C [4]. In terms of toxicity, while the single components of EGaIn are commonly used (Indium has been used in dental fillings, while Gallium is a trace nutrient), the alloy is potentially corrosive [36]. According to the ALARP principle [11], the risk of spillage was kept low by using 9g of EGaIn for each blob that, once deployed in the set-up, could be re-used many times. Sodium hydroxide was preferred to the chloridic acid used in [25]: NaOH still removes the gallium oxide, promoting the wetting of the liquid metal, but it is safer to use. Again, the risk of spillage is mainly present during experiment preparation and was kept as low as reasonably practical using appropriate personal protective equipment (i.e., gloves and safety glasses).

Electrode Array Design

Fig. 3 and Fig. 4 show the top view and the back view of our 7x7 graphite electrode array display. The prototype fixtures and the display surface are built using laser-cut acrylic sheets.

Particular care was taken in selecting the material for the electrodes, as they have to survive corrosion due to both electrolysis (i.e., oxidization) and the selected liquid metal. For instance, although copper is a popular electrode material, because of its high conductivity and better strength than silver [14], it is inferior in terms of oxidization resistance and is likely corroded by EGaIn [3]. On the other hand, platinum would be the ideal material, because it combines high conductivity with excellent corrosion and erosion resistance. Due to its high cost, however, platinum would only be applicable to displays featuring a limited number of electrodes [48] and would therefore make scaling-up the technology difficult.

In addition, during our preliminary experiments with other metals (e.g., stainless steel, gold-plated electrode, printed silver), we observed that the EGaIn blob had a tendency to adhere to metallic electrodes (probably due to ongoing corrosion), so we moved to non-metallic substances. We selected Carbon/Graphite: these electrodes are highly conductive, show superior resistance to electrochemical erosion/corrosion than metals and are still cost-effective [14]. It is also reported that Graphite helps liquid metal blobs to be wet and stay flat, hence this material appeared as the ideal electrode option for studies – like this one – focused on the shape deformation of liquid metals [13, 44].

We embedded 49 units of 5.4 mm diameter graphite electrodes into the acrylic display surface and built a 7x7 grid electrode array at the pitch of 10.4 mm. The whole display area is 83 mm x 83 mm as shown in Fig. 3. To prevent the leakage of electrolyte solutions, we deployed a silicone glue to fill the gaps between graphite electrodes and the acrylic substrate. This glue also enforced the strength of graphite electrodes, as Fig. 4 shows. Each graphite rod was wired through a laser-cut acrylic adapter individually. The height and balance of the display surface was adjustable with respect to the ground by rotating the screws of four supporting legs.

Liquid Metal Control System

Fig. 5 shows our prototype liquid metal control system. We deployed pulse width modulation (PWM) driver arrays to supply voltage signal to electrode arrays. We used four PCA9685 16-channels PWM drivers and twenty-five L293 dual-channel

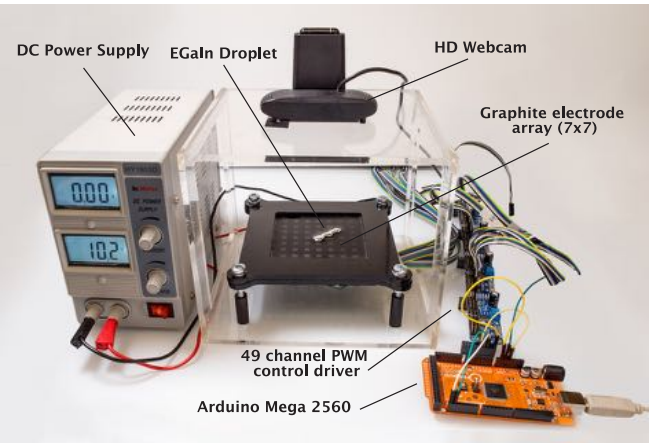

Figure 5. Experimental setup of the implemented system. We used a 49 channel PWM driver controlled by an Arduino microcontroller to affect the voltages of the 7x7 graphite electrode array. This information is then tracked and sent back to the computer.

H-bridge motor drivers. We used Arduino Mega 2560 to control the voltage levels of the electrode arrays. A server PC shows a simple graphical user interface for users to control liquid metal and commands the Arduino Mega via serial communication to signal programmed voltage patterns to electrode arrays (see next section).

We set a HD web camera above the display to track the positions of the 49 electrodes as well as the shape and position of the liquid metal. This allowed us to build a camera-feedback system to visualize the relative position of electrode arrays and liquid metal as well as the status of liquid metals. It also helps novice users to manipulate liquid metals easily to achieve the desired shape. In the next section, we introduce our control algorithms and GUI design.

Control algorithms and GUI

Fig. 6 shows our control algorithm to deform liquid metal in a desired shape. As we explained in the Programmable Liquid Matter section, we can deform liquid metal from Anode (High Voltage electrode) to Cathode (Low Voltage electrode). Since Cathode attracts liquid metal and Anode keeps liquid metal in a wet, flat state, the simplest algorithm to control liquid metal is to switch only one selected electrode as Cathode (low voltage) and sets all other electrodes as Anodes (high voltage). The relative voltage difference decides the speed of liquid metal deformation. Since liquid metal shrinks to a marble shape when it is in contact with a Cathode, we must carefully track it at each step of the deformation. Just before the liquid metal passes the Cathode, we must smoothly switch the voltage from Low to High at the passing electrodes as illustrated by the green electrodes in Fig. 6. Green electrodes present a trace of selected Cathodes and are always set as Anode (high voltage) to keep liquid metal wet and flat (the lowest surface tension state).

To control liquid metal, we propose three different control modes: manual control, camera-assisted control and mirrored control. Manual mode is as explained in the simple control

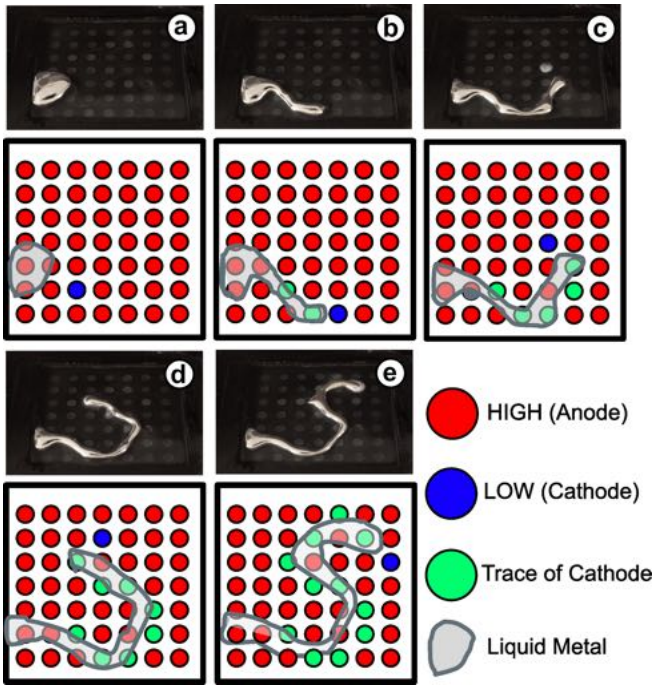

Figure 6. Basic electrode array control algorithm to make alphabet letter "S".

algorithm, "carrot and stick" style. This method works well unless liquid metal contacts the cathode to break the shape.

To avoid unnecessary direct contact with the cathodes, we implemented a camera-assisted system. As Fig. 7 shows, the camera feedback system helps users by visualizing electrode array position and liquid metal shape and position. We deployed a standard contour tracking algorithm to track the liquid metal and automatically deselect cathode electrode when the liquid metal is reached. The size and stability of liquid metal are captioned with numbers. The breaking risk points are visualized by red dots. We found that liquid metal starts breaking more often after expanding to the size of an area of more than five times its original size. Tracking areas by camera assist also helps novice users to notice the limit of deformation size.

Mirror mode helps users to draw a symmetric shape by controlling two symmetric electrodes to the central line by clicking only one electrode. As Fig. 8 shows, this helps users to draw a symmetric shape (e.g,. heart shape) in less than half the time of clicking entire outline points of the target shape.

APPLICATION

As Wakita et al. explored with ferromagnetic fluids, fine-shape-control of liquid metal has many potential applications for autonomous tangible interface, blob animation and digital painting for media artists [42, 43]. Although we have not explored the easy solidification property of liquid metal at room temperature, we can facilitate our liquid metal shape control system as a rapid prototyping printer to fabricate accessories or gadgets.

The most interesting and unique application of liquid metal is opened to the electronics design. The high conductivity

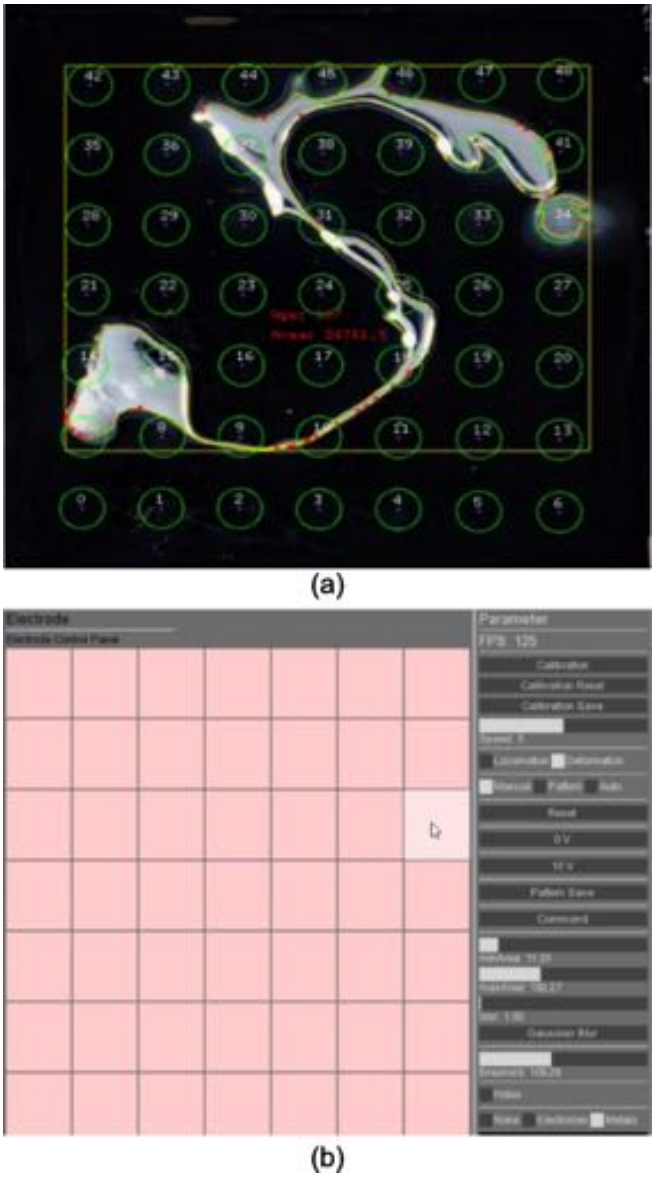

Figure 7. User interface of the liquid metal control system. (a) Camera view feedback image shows the visualized electrode array position and liquid metal shape and position. The size and stability of the liquid metal is captioned with numbers. A selected Cathode is visualized with a yellow outline. The breaking risk points are visualized by red dots. (b) A simple button and slider based GUI to control liquid metal. Each rectangular button represents corresponding electrode. Red is the highest voltage and white is the lowest voltage.

($\sim 3.4 \times 10^6\,\mathrm{S/m}$)[36, 38], dynamic range shape and deformation possibilities of EGaIn show promising applications for shape changing, reconfigurable electronic circuits, as shown in Figs. 9 and 10. Since liquid metals are connected to positive voltage with electrically equipotential body, electronic components such as LEDs can be dynamically switched by liquid metal deformation. Liquid metals free from path tracing control can expand the potential of a dynamically programmable circuit as well as actuator signal control channels. One of the design limitations here, is the electrolyte solution (e.g.,

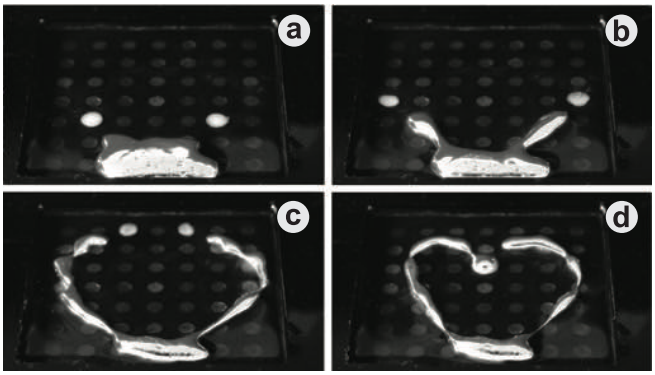

Figure 8. Heart shape drawing with mirror mode electrodes control.

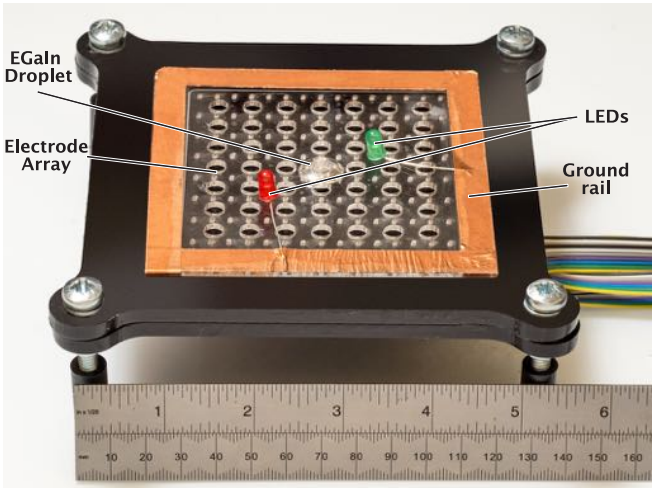

Figure 9. Reconfigurable LED circuit using controlled conductive liquid metal. LEDs are placed on top of the supporting acrylic sheet. Since oxygen and hydrogen gas are essential for electrolysis reaction which drives deformation of liquid metal, we punched many holes in this acrylic sheet for ventilation. The outer edge of the acrylic sheet is coated with a conductive copper tape which works as a ground. A cathode leg of LED is connected to this ground and the anode leg is fixed under the acrylic sheet.

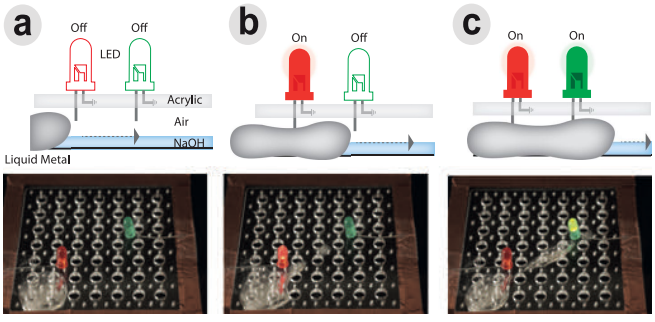

Figure 10. Side view and live view of reconfiguring circuit to switch LEDs with conductive liquid metal. The LEDs can be lit by making connections to the positive electrode through moving conductive liquid metal.

NaOH), which is also conductive, so the space between components and the conductive electrolyte solution must be carefully designed to connect only with liquid metal as Fig. 10 (top) shows.

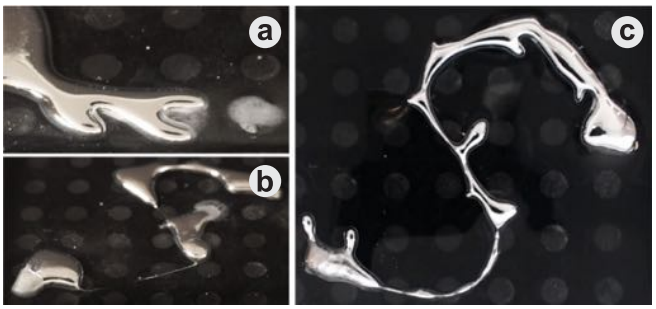

Figure 11. Challenges of Liquid Metal Shape Control: (a) Branching (Finger Instability) (b) Splitting (c) Liquid Metal Body Interference.

DISCUSSION

Although our camera-tracking based GUI control system facilitates users to physically draw any desired path with liquid metal, there are still a couple of challenges to resolve for stable rendering. As Fig. 11 shows, there are three main problems inherent to liquid metal deformation: finger-shaped instability (branching), splitting and liquid metal body interference. We have seen liquid metal easily branching at cathodes where H_2 gas is generated and causes liquid metal branching to multiple trees. We also occasionally see this phenomena in other places than cathodes at random outer points. The phenomena become more significant at higher applied voltage than around 5V.

Splitting is a critical problem of liquid metal shape control since it splits the body to multiple liquid metal marbles because of higher surface tension at smaller size. We have seen more splitting at cathode areas and find it occurs more often with a lesser volume of liquid metals. Self-body electrode interference stops liquid metal's head motion toward the target cathode and body parts instead get attracted because of equipotential conductive surface of liquid metals. To resolve this problem, we need more precise voltage distribution control around liquid metals, which help only the head of liquid metal get more attracted to the target point by localised descent gradient force of the applied electrostatic filed.

In this prototype system, we did not implement a reservoir system to supply liquid metal on demand and the maximum size of liquid metal capacity is limited. An external liquid metal reservoir with pumping functionality could realize larger scale shape rendering with liquid metal and could help us to explore solid geometry rendering instead of just the outline shape.

CONCLUSIONS

In this paper, we explored programming liquid matter for customisable and interactive animation with a dynamic electric field. We implemented a novel prototype that can alter the shape of liquid metal by moving it along a desired path. By creating a hardware framework and a graphical user interface to promote interactive visualisations, we demonstrated novel manipulation of liquid metal with a vision to expand the work on shape changing, programmable material and consider its use as a method for providing a programmable electric circuit. We discuss the current limitations of our designs in the context of the fingering and splitting of the material, towards optimising future designs. While this work is in its early stages, we have seen compelling evidence of detailed 2D control of liquid metals and have therefore laid the foundations for what we hope to be a rich area of future work.

ACKNOWLEDGEMENTS

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