Programmable Liquid Matter: 2D Shape Drawing of Liquid Metals by Dynamic Electric Field

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Abstract
We present a programmable liquid matter which can dynamically transform its 2D shape into a variety of forms and present unique organic animations based on spatio-temporally controlled electric fields. We deployed a EGaIn (Gallium indium eutectic alloy) liquid metal as our smart liquid material since it features a superior electric conductivity in spite of a liquid state and presents a high dynamic range of surface tension and 2D area controlled by applied voltage strength and polarity. Our proposed liquid metal shape and motion control algorithms with dynamically patterned electric fields realize path tracing organic animation. We demonstrate an interactive 7x7 electrode array control system with a computer vision based GUI system to enable novice users to physically draw alphabet letters and 2D shapes by unique animatronics of liquid metals.

Author Keywords
Liquid metal; Programmable Matter; Gallium; Blob Animation; Electric Field; Marangoni Effect; Shape Changing Display; Smart Material; Animatronics

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

Introduction

Interactive surfaces using programmable matter [3] is a long-term vision dreamed by many display and robotic researchers. It could enable physical objects to be programmed and controlled to design visual appearance, various tangible shape and on-demand functionality just as we manipulate digital information.

Materials such as clay, gel, soap bubble [1] and ferrofluid [5] have been used to make programmable surfaces. A promising candidate in this direction is the liquid metal which has attracted many researchers for its unique properties, e.g., voltage controlled surface tension, high conductivity in liquid state and liquid-solid phase transition [2,4]. However, the locomotion and deformation of liquid metal is highly nonlinear and challenging to manipulate for novice users.

We present a 7x7 electrode array based liquid metal control display and propose a graphical user interface and closed-loop control approach based on camera tracking model to assist users to easily manipulate the liquid metals to physically design and render expected 2D shapes with enjoyment of the lifelike drawing process.

Programmable Liquid Matter

A EGaIn (Gallium indium eutectic alloy) liquid metal is highly conductive and at the same has high surface tension in the electrolyte solution. When the liquid metal blob is immersed in the basic electrolyte solution (e.g. NaOH), EGaIN reacts with NaOH and produces negatively charged ions ($Ga(OH)_4^-$) on the surface. It induces a uniform positive charge from distribution on its surface as shown in Figure 1(a). In the equilibrium state of the surface force between

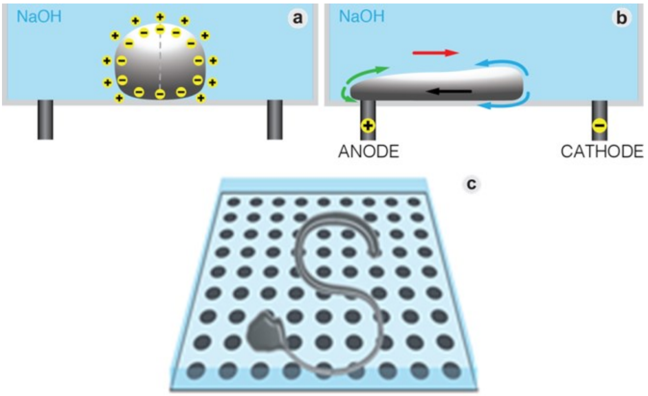

Figure 1. Liquid Metal Motion Mechanism: (a) Normal state without voltage (b) Deformation with positively applied voltage (c) Liquid Metal Control by Electrode Array

negative charge (i.e. liquid metal side) and positive charge (i.e. NaOH side), the shape tends to become the most stable form of symmetric sphere. When the liquid metal blob comes in contact with the anode, the surface charge distribution now becomes positively charged. As a result, the surface of the blob gets oxidized and losses surface energy and surface tension. The liquid metal blob readily deforms from its spherical shape and flattens on the surface. The positively charged blob also spreads towards the cathode following the electric field direction, as shown in Figure 1(b). Our proposed approach is to move the liquid metal blob along the surface of discrete electrode grid array while maintaining connectivity to create the desired shapes as shown in Figure 1 (c). We achieve this using the spontaneous deformation and locomotion mechanisms of the liquid metal described above by programming the voltage signal applied to the electrode arrays in a suitable prototype presented next.

Prototype system of liquid metal control

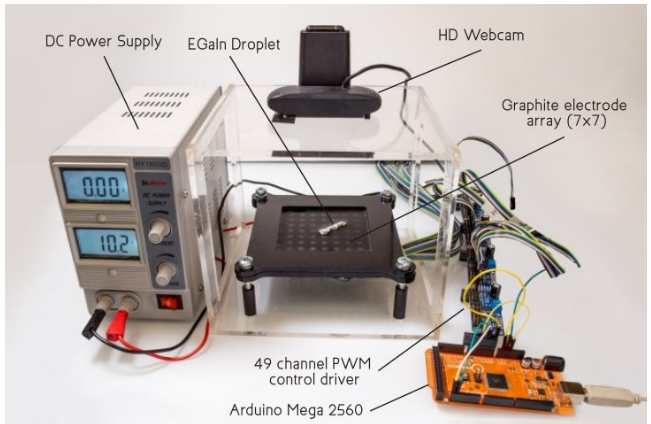

Figure 2. We use a 49 channel PWM driver controlled by an Arduino microcontroller to affect the voltages of the 7x7 graphite electrode array. The position and shape of liquid metal is tracked by a HD Web camera set up over the display surface.

The 7x7 electrode arrays display and the prototype system we built to demonstrate our approach of programmable liquid metal is shown in Figure 2. We used 9 g of EGaIn to create the liquid metal blob. The prototype fixtures and the display surface are built using lasercut acrylic sheets. Graphite rods with diameter of 5.4 mm embedded in the display surface are used as the electrodes to avoid adhesion of EGaIn blobs to them. 1M NaOH is used as the electrolyte. We used 49 electrodes to build an 7x7 grid with pitch of 10.4 mm and effective size of 83x83 mm display area. A DC voltage supply with pulse width modulation (PWM) electronics was built to control the voltage signal applied to individual electrodes. Four PCA9685 16-channels PWM drivers with twenty-five L293 dual-channel H-bridge motor drivers are used in the circuit. An Arduino Mega 2560 is used to control the voltage signal applied to electrodes from a PC which allowed us to program the deformation and locomotion of the blob at each location on the surface with GUI, as we discuss more details in the next section. A HD web camera above the display surface is used to track the 49 electrodes' positions as well as EGaIn shape and position using a blob tracking algorithm with a PC.

Liquid metal manipulation GUI

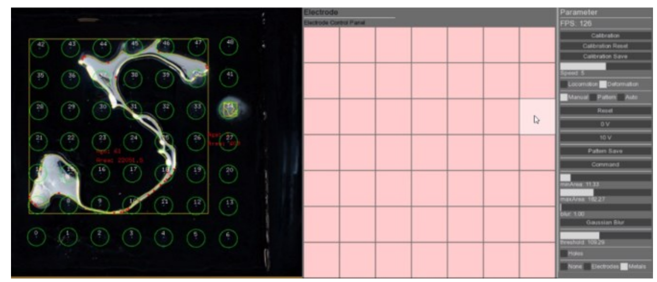

Figure 3. Graphical User Interface of Liquid Metal Control System.

Figure 3 shows our GUI screenshot image while a user was trying to draw an alphabet letter "S". The left window shows a web camera image and calibrated electrodes position with circled areas and tracked liquid metal's position and convex hull shape. We deployed OpenCV's standard contour tracking algorithm and displayed an outline connected by convex hull points and defect points. The right window shows 7x7 Matrix Buttons corresponding to each electrode to control the voltage. Users can control each voltage either by 1 bit (LOW: 0V or HIGH: 10V) with a single clicking or 4020 bits voltage control by PWM whose active ratio is controlled by a slider UI component.

We implemented three different control modes: manual control, camera-assisted control and mirrored control. Since liquid metals move toward from anode to cathode as we explained in the Programmable Liquid Matter section, manual mode set all electrodes as anode (High voltage electrode) as default and the clicked electrode as a cathode (Low voltage electrode) and move liquid metal toward the selected point. Liquid metals become unstable and sometimes break when it contacts with the target cathode because liquid metal is high conductive and make short circuit. To avoid unnecessary direct contact with cathode and track the unstable point (such as thinner part which easily break), camera-assisted control helps user to find distance between nearest cathodes and moving head part as well as potential breaking points at the thinnest blob body.

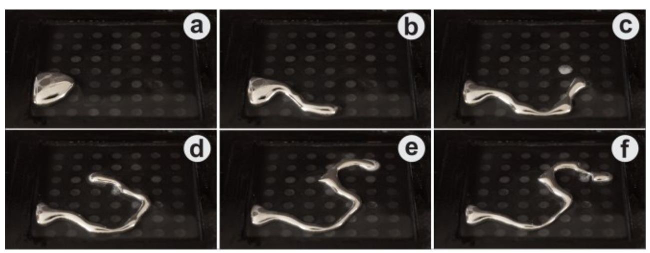

Figure 4. Process of drawing a letter "S" with EGaIn

Since liquid metal start breaking more often after the size becomes larger than the twice, tracking the size by camera assisted also help novice users to successfully draw continuous nonlinear shape like alphabet letter "S" without breaking as Figure 4 shows. Mirror mode helps users to draw a symmetric shape (e.g. Heart Shape) by controlling two symmetric electrodes to the central line by clicking only one electrode.

Conclusion
We explored programming liquid matter for customizable and interactive physical material 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 create interactive visualizations, we present novel manipulation of liquid metal with a vision to expand the work on shape changing, programmable material.

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