LIME: LIquid MEtal Interfaces for Non-Rigid Interaction

Qiuyu Lu, Chengpeng Mao, Liyuan Wang, Haipeng Mi
Information Art & Design, Tsinghua University
Beijing 100084, China
{lu-qy14, mcp13, wang-ly14}@mails.tsinghua.edu.cn, haipeng.mi@acm.org

ABSTRACT

Room-temperature liquid metal GaIn25 (Eutectic Gallium-Indium alloy, 75% gallium and 25% indium) has distinctive properties of reversible deformation and controllable locomotion under an external electric field stimulus. Liquid metal's newly discovered properties imply great possibilities in developing new technique for interface design. In this paper, we present LIME, LIquid MEtal interfaces for non-rigid interaction. We first discuss the interaction potential of LIME interfaces. Then we introduce the development of LIME cells and the design of some LIME widgets.

Author Keywords

Liquid Metal; Shape-Changing; Haptic Feedback; Non-Rigid Interface

ACM Classification Keywords

H.5.2. Information interfaces and presentation: Prototyping

INTRODUCTION

In the field of HCI, researchers have started to investigate smart materials and apply them to design novel interfaces. Smart materials, which are capable of changing their chemical or physical properties while under a certain stimulus [11], have been used to design novel interfaces. Shape memory alloy [1,2,10] and humidity sensitive biological material [13] have been applied to shape-changing interfaces and texture-changing interfaces. Ferromagnetic fluid [6] and thermoresponsive hydrogel [8] have been utilized for stiffness-changing interfaces. Such researches have explored new technique for interface design, enabling new HCI semantics that have been used in manifesting of digital information, offering dynamic affordances, providing haptic feedback, and affording different functionalities [4,5,8,12].

Niiyama et al. have used liquid metal as a medium of mass transfer in interface design. With an extra pump, this work realized a passive transfer of liquid metal [9]. Recently, some unique properties of liquid metal have been revealed. Under external electric field stimuli, liquid metal GaIn25 shows a capability of reversible shape-changing and controllable locomotion [7,14]. This distinctive mechanism inspired us to develop novel interaction techniques.

With our work, we are contributing by introducing the distinctive properties of liquid metal for interface design, discussing interaction potential of LIME interfaces, and presenting the design and development of LIME cells and a number of LIME widgets.

PROPERTIES OF LIQUID METAL

GaIn25 is room temperature liquid metal with a melting point of ~15.5°C and a density of ~$6.35 g/cm^3$ [3]. These physical parameters are adjustable by regulating the proportion of alloys.

A GaIn25 droplet can transform from a sphere to a large thin film and vice versa, under the stimulation of external electric field when in alkaline or acidic electrolyte solution (e.g. NaOH solution). The variation of surface area can reach up to 5 times (Figure 1). Besides, the droplet tends to flow towards the cathode while deforming (Figure 2). The deformation is caused by the change in surface tension. Electrochemical oxide combines on the surface of a liquid metal droplet under an external electric field stimulus, leading to a decline of surface tension from ~$500 mj/m^2$ to near zero. The surface tension reconverts when electric field is removed so that oxide is chemically dissolved by NaOH solution. Furthermore, the oxidation of liquid metal can even be affected by the distribution of the electric field

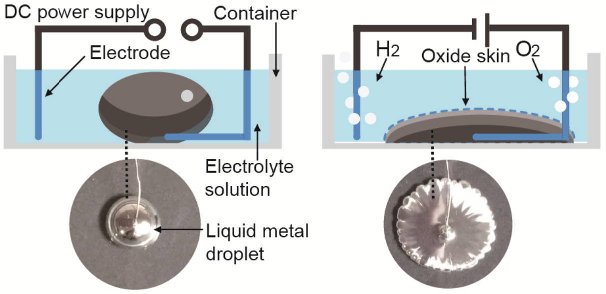

Figure 1. Working mechanism of the liquid metal's reversible deformation

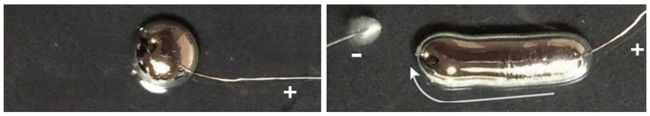

Figure 2. Locomotion caused by the electric field

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in the solution, as a result, a liquid metal droplet is able to be actuated to perform locomotion [7,14].

Generally, deformability and reversibility of liquid metal are used to describe its capability of deformation and locomotion. Deformability (D) represents the maximum change of the projected area and the speed of deformation. The major factors affecting D include the voltage (V) and the concentration of NaOH (C). Usually, an increasing V leads to an increasing D. However, after V exceeds a threshold, D decreases as overmuch accumulation of solid oxide hampers the deformation. Meanwhile, increasing C also leads to an increasing D, because oxide accumulation increases accordingly. Typically, D will tend to keep stable when C exceeds ~1mol/L since the increments of oxide dissolution counteracts the increments of oxide accumulation [14].

Reversibility (R) indicates the speed of reversion. The major factors affecting R include V and C, and the exposure duration to the electric field (T). Similar to the deformability, an increasing C leads to an increasing R. However, increasing either V or T will decrease R, because more oxide will accumulate [14].

DEVELOPMENT OF LIME INTERFACES

Interaction Potential of LIME Interfaces

Considering the distinctive properties of liquid metal, here we describe the interaction potential of LIME interface as *visual effect* and *dynamic haptic feedback* (Figure 3).

Visual effect – The capability of tremendous projected area change enables the possibility of *visual effect augmentation* in a physical form. For example, information behind can be hidden/revealed, or marked as checked/unchecked. Besides, the flickering of a LIME droplet may draw attention or indicate the progress, while the frequency can suggest the importance or urgency level. Moreover, locomotion of substances will guide a shift of attention.

Dynamic haptic feedback – Liquid metal with very high surface tension can be felt uniquely when touched. It feels like very soft gel. Its natural properties afford interactions like pressing and pushing, and provide tactile feedbacks with unique feeling to the touch. An interesting fact is that the tactile feedback will almost completely disappear if electric field is applied. With this special property, it is possible to make interfaces with *dynamic haptic feedback*, which can provide tactile feedbacks only when needed. Additionally, active transfer of liquid metal can also provide a haptic feeling of weight redistribution.

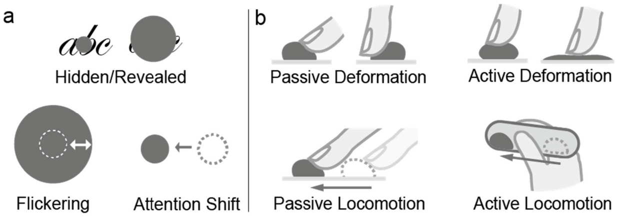
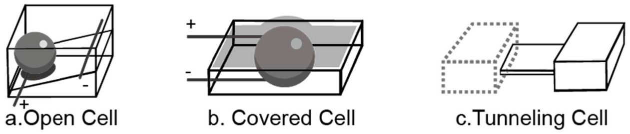


Figure 3. Interaction potential of LIME interfaces: a) Visual effect, b) Dynamic haptic feedback

Elemental Forms of LIME Cell

The liquid metal needs electric field and solution environment to work normally. We have designed a series of LIME cells, which are containers with electrodes embedded. For each cell, 1mol/L NaOH is injected to submerge the electrodes. The LIME cells are the basic building bricks for LIME interface. More specifically, there are three forms of LIME cell (figure 4).



a.Open Cell b. Covered Cell c.Tunneling Cell

Figure 4. Three elemental forms of LIME cell

Open cell

The open cell is designed to have a liquid metal droplet being able to fully cover the cell when activated, and shrink to almost invisible when deactivated. Smaller droplet has a better invisibility, but increases implementation difficulties. Taking this trade-off into account, we have designed the open cell with an inner dimension of L9×W9×H9mm, and injected ~0.3ml liquid metal into the cell. In order to keep the droplet contacting with the electrode, the bottom is designed as a gentle slope (figure 4a). The deformation time is ~0.5s and the restoring time is ~0.3s when a 5V pulse stimulus is applied, with a peak current of ~0.15A.

Covered cell

The covered cell has a thin film lid on the top, allowing users to touch, push and feel the liquid metal directly and safely. It is shallow enough (inner height below 4mm) so that the droplet can jack up the lid when idle (figure 4b). The size of a covered cell is relatively flexible, and can be designed to fit a specific quantity of droplet. Particularly, a L10×W10 cell is appropriate to afford a 4-5ml liquid metal droplet, which has a size to fit one's fingertip. If deformation is also required, the size of the cell has to be increased to L20×W20. In this case, the deformation time is ~0.5s and the restoring time is ~0.4s when under a 5V pulse stimulus, and the peak current is ~0.7A.

Tunneling cell

The tunneling cell has a tunnel for liquid metal to transfer between cells (figure 4c). An ordinary tunnel (D ≈ 5mm) enables transfer under either manipulations of users (e.g. pushing, tilting) or electric stimuli. However, a cramped tunnel (D ≈ 1mm) only allows electrically controlled transfer. Because of the high surface tension, one cannot easily move a liquid metal droplet across the cramped tunnel by pushing or tilting. Interestingly, electric field decreases the surface tension. As a result, the liquid metal can even be attracted into the cramped tunnel towards the cathode. In a typical experiment, we let 2ml liquid metal flow across a cramped tunnel (L25×W10×D1.2mm) under a 10V stimulus. The current rises from ~0.2A to ~0.9A as the liquid metal being approaching to the cathode. The time that 70% liquid metal (~1.4ml, 8.89g) flowed to the target cell is ~6s. Residual phenomenon has been observed during experiments, especially when the cell at the beginning of the tunnel has a bigger size.

LIME cell as a sensor

With a specific configuration of electrodes, a LIME cell is capable to become a sensor, which can detect finger manipulations and passive locomotion of liquid metal. The resistivity between two electrodes will dramatically decreases from ~5.8 Ω·cm to ~29.4×10^{-6} Ω·cm when they are connected by liquid metal.

Designing LIME Widget

Based on the LIME cells, we are able to design a number of LIME widgets. Each LIME widget consists of a group of LIME cells and a micro-controller board, so that each cell of the widget can be controlled separately.

Shutter

A shutter is composed of a matrix of open cells, which can switch between transparent and opaque (Figure 5). A globally switched shutter is capable to dynamically cover or reveal objects or information behind it. Also, with a specifically designed control sequence, the shutter widget is even able to achieve a fancy revealing effect. Moreover, with flickering effect the widget can provide an emphasis to attached information.

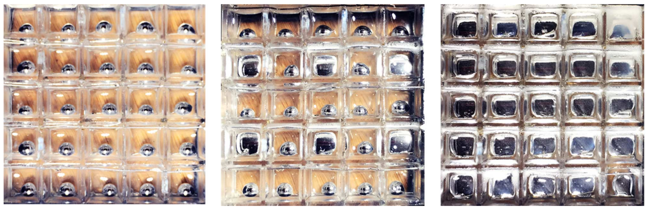


Figure 5. A shutter widget

Selection Widgets

A Checkbox is composed of a row of open cells. Because it is normally transparent, a checkbox widget can be attached to any surface such as a post-it memo. Different expressions of each check box may indicate different status of relevant information, such as checked (opaque), unchecked (clear) and ongoing (flickering) (Figure 6a). A radio button is composed of a row of tunneling cells. The liquid metal droplet can traverse actively to a specific position, emphasizing the selected item (Figure 6b).

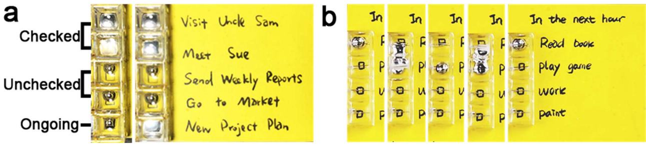


Figure 6. Selection widgets.
a) A checkbox widget, b) A radio button widget

Tactile-Affordance-Changing Widget

A tactile-texture-changing widget is composed of covered cells. It can change haptic affordance dynamically, creating keyboards with different layouts (Figure 7).

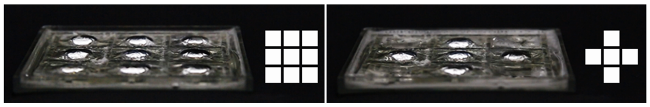


Figure 7. A tactile-affordance-changing widget

Controlling Widgets

Covered cell provides a non-rigid tactile input, enabling implementations of controlling widgets. A thumbstick (Figure 8a) has one electrode in the middle and four in the corners embedded to detect finger input. Furthermore, utilizing the passive and detective locomotion of liquid metal, slider (Figure 8b) and knob widget (Figure 8c) can be implemented by combining covered and tunneling cells. Electrodes are embedded on the bottom of each cell to detect the locomotion of the droplet.

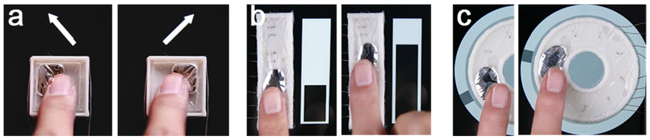


Figure 8. Controlling widgets.
a) A thumbstick, b) A slider, c) A knob.

Weight-Changing Widget

The weight-changing widget can provide haptic feeling of weight redistribution. It consists of 3 big tunneling cells. To visualize the weight redistribution, a fulcrum is put in the middle of the widget. When activated, liquid metal will transfer between different cells and the widget can move itself up and down (Figure 9).

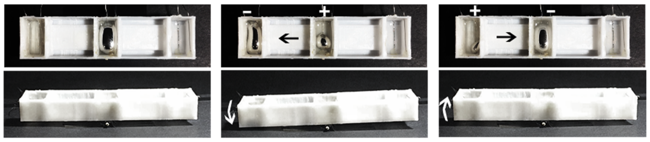


Figure 9. A Weight-changing widget

DISCUSSION

A LIME widget with visual effect augmentation (e.g. a shutter) plays a role of an additional information layer adding new interaction styles to the environment, physical objects or other existing interfaces. A large scaled shutter can be integrated with the skylight, generating shadows on other surface and conveying information in a delicate and nonintrusive way [1]. Shutters may also mask to regular papers, making the contents on them interactive through occlusion-changing.

A LIME widget with dynamic haptic feedback can be combined with regular devices to provide tactile feedback. It can be attached to displays, generating physical buttons or sliders. Besides, weight-redistributing widget can be integrated with handheld devices, adding a new dimension of interaction. The haptic feeling of weight redistribution has a potential to enhance screen content and enable eye-free interactions.

One of the limitations of LIME interface is the generation of gas on the electrode. To deal with this problem, the vent holes must be reserved. This explains that the LIME cell cannot be completely sealed up at this stage. However, elaborate discharge ducts can be designed to avoid the liquid leakage problem, enabling tilt of the LIME cell to a certain range. One more limitation is the visual interference caused by the gas generated on the electrodes. Lowering the voltage can reduce the interference, but at the cost of longer response time of deformation. For example, when the voltage of the covered cell is lowered to to 2.5v, the response time will increase to ~1s.

Slight tilting is possible with our prototype. However, in order to achieve a better spreading of LIME droplet all over the bottom of the cell, and to keep the droplet having a good contact with the electrode it is better to keep LIME interfaces horizontally.

FUTURE WORK

The performance of LIME interface can be improved technically. Khan et al. suggested a method of replacing alkaline solution with neutral salt solution and dissolving the oxide by polarity reversal. This method can be applied in the situation that liquid metal is required to keep low surface tension most of the time. The energy cost and gas generation can be reduced [7].

We have preliminarily explored combination of different LIME cell forms through the slider bar widgets. Different forms of cell can be integrated more elaborately. For instance, the covered cells and tunneling cells can be integrated to actuate liquid metal to a certain location and provide haptic feedback as needed.

Liquid metal still have other special properties. For example, it has adjustable melting point, which has a potential to develop stiffness-changing interface. The full view of the LIME design space remains future investigation.

CONCLUSION

This paper introduces electrically controllable liquid metal as an enabling technology for designing interfaces. We explore the interaction potential of LIME interface, present the development of LIME cells according to the properties of liquid metal, and demonstrate several LIME widgets that enable different interactions. We do believe that LIME has huge potentials for HCI.

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REFERENCES

1. Coelho, M. and Maes, P. Shutters: a permeable surface for environmental control and communication. In *Proc. TEI '09*, 13-18.
2. Coelho, M., Ishii, H., and Maes, P. Surflex: a programmable surface for the design of tangible interfaces. In *Proc. CHI EA '08*, 3429-3434.
3. Dickey, Chiechi, R.C., Larsen, R.J., Weiss, E.A., Weitz, D.A., and Whitesides, G.M. Eutectic Gallium-Indium (EGaIn): a liquid metal alloy for the formation of stable structures in microchannels at Room Temperature. *Adv. Func. Mater. 18*, 7 (2008), 1097–1104.
4. Majken K. R., Esben W. P., Marianne G. P., and Kasper H. Shape-changing interfaces: a review of the design space and open research questions. In *Proc. CHI '12*, 735-744.
5. Ishii, H., Lakatos, D., Bonanni, L., Labrune, J.-B Radical atoms: beyond tangible bits, toward transformable materials. *Interactions 19*, 1 (2012), 38–51.
6. Jansen, Y. Mudpad: fluid haptics for multitouch surfaces. In *Proc. CHI EA '10*, 4351-4356.
7. Khan, M.R., Eaker, C.B., Bowden, E.F., and Dickey, M.D. Giant and switchable surface activity of liquid metal via surface oxidation. *Proceedings of the National Academy of Sciences 111*, 39 (2014), 14047–14051.
8. Miruchna, V., Walter, R., Lindlbauer, D., Lehmann, M., Klitzing, von, R., and Müller, J. GelTouch: localized tactile feedback through thin, programmable gel. In *Proc. UIST '15*, 3–10.
9. Niiyama, R., Yao, L., and Ishii, H. Weight and volume changing device with liquid metal transfer. In *Proc. TEI '14*, 49–52.
10. Probst, K., Seifried, T., Haller, M., Yasu, K., Sugimoto, M., and Inami, M. Move-it: interactive sticky notes actuated by shape memory alloys. In *Proc. CHI EA '11*, 1393-1398.
11. Vyas, D., Poelman, W., Nijholt, A., and Bruijn, A.D. Smart material interfaces: a new form of physical interaction. In *Proc. CHI EA '12*, 1721-1726.
12. Yao, L., Niiyama, R., Ou, J., Follmer, S., Della Silva, C., and Ishii, H. PneUI: pneumatically actuated soft composite materials for shape changing interfaces. In *Proc. UIST '13*, 13–22.
13. Yao, L., Ou J., Cheng, C.-Y., Steiner, H., Wang, W., Wang, G., and Ishii, H. bioLogic: natto cells as nanoactuators for shape changing interfaces. In *Proc. CHI '15*, 1–10.
14. Zhang, J., Sheng, L., and Liu, J. Synthetically chemical-electrical mechanism for controlling large scale reversible deformation of liquid metal objects. *Scientific Reports 4*, (2014), 7116.