# Tangible Drops: A Visio-Tactile Display Using Actuated Liquid-Metal Droplets

**Deepak Ranjan Sahoo,[1] Timothy Neate,[1] Yutaka Tokuda,[2]**
**Jennifer Pearson,[1] Simon Robinson,[1] Sriram Subramanian,[2] Matt Jones[1]**
[1] FIT Lab, Swansea University, UK
{ d.r.sahoo, timothy.neate, j.pearson, s.n.w.robinson, matt.jones } @swansea.ac.uk
[2] Interact Lab, University of Sussex, UK
{ y.tokuda, sriram } @sussex.ac.uk

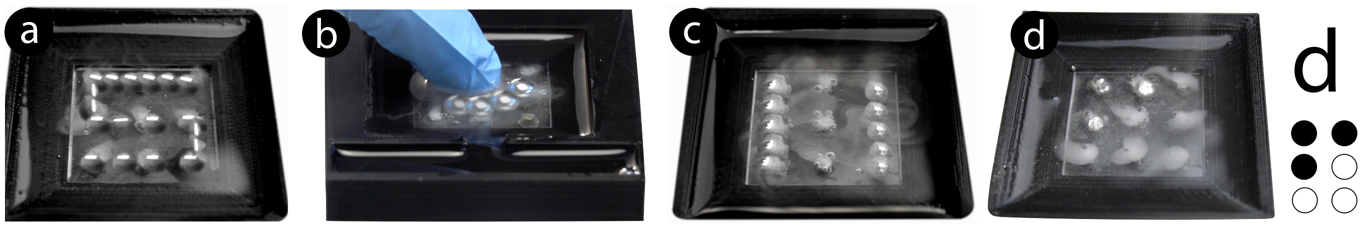


**Figure 1. (a) A (timelapsed) visual display showing animated letter "S" using locomotion, and (b) a (timelapsed) tactile display with direction feedback using vibration and locomotion of a liquid metal drop. (c) A timelapsed visio-tactile equalizer widget and (d) a dynamic Braille display.**

## ABSTRACT
We present Tangible Drops, a visio-tactile display that for the first time provides physical visualization and tactile feedback using a planar liquid interface. It presents digital information interactively by tracing dynamic patterns on horizontal flat surfaces using liquid metal drops on a programmable electrode array. It provides tactile feedback with directional information in the 2D vector plane using linear locomotion and/or vibration of the liquid metal drops. We demonstrate move, oscillate, merge, split and dispense-from-reservoir functions of the liquid metal drops by consuming low power (450 mW per electrode) and low voltage (8–15 V). We report on results of our empirical study with 12 participants on tactile feedback using 8 mm diameter drops, which indicate that Tangible Drops can convey tactile sensations such as changing speed, varying direction and controlled oscillation with no visual feedback. We present the design space and demonstrate the applications of Tangible Drops, and conclude by suggesting potential future applications for the technique.

### Author Keywords
Tangible Drops; Liquid Metal; Tactile Feedback; Kinetic Interface; Rheological Interface; Non-Rigid Interface; Programmable Matter

### ACM Classification Keywords
H.5.2. User Interfaces: Haptic I/O; Prototyping; User-centered design


*CHI 2018,* April 21–26, 2018, Montreal, QC, Canada

ISBN 978-1-4503-5620-6/18/04. . . $15.00
DOI: https://doi.org/10.1145/3173574.3173751

## INTRODUCTION
Current interactions with mobile devices are largely confined to pressing, swiping and gesturing on flat glass surfaces to manipulate digital content. In comparison to physical interfaces and controls, these high-resolution capacitive touch-screens allow for greater user interface diversity and flexibility, but as a result offer little in the way of tactile feedback, leaving the rich sensory capabilities of our hands and bodies particularly under-utilised. As Bret Victor fittingly describes it, this interaction technique is often little more than "pictures under glass" [54], providing none of the tangibility benefits of physical, tactile interfaces.

Much research of late has aimed to tackle this trade-off between physicality and mutability. The ultimate goal is to develop interfaces that can provide real-time physical feedback, creating truly three-dimensional interfaces, and producing new, more tangible computing experiences. Tangibility and tactile feedback have been shown to offer many benefits over touch-screen user interfaces, such as the reduced need for visual attention [19], and an increased level of task efficiency [53]. Tangible controls—for example on a flight deck or an audio mixing desk—nearly always excel when compared to their touchscreen counterparts [39, 53, 55].

This lack of mutability in tangible interfaces, and the lack of tangibility in digital interfaces, has led to the development of shape-changing interfaces, with an ultimate aim to connect the physical world more directly to the digital content we use and manipulate, as outlined in Ishii's vision of tangible bits [16]. The majority of current work on shape-change focuses on electromechanical devices to provide dynamic feedback – for example, through actuation of rods [10, 39], or filling a membrane with fluid [12, 61]. However, recent work which seeks to develop new interfaces has also taken inspiration from unconventional areas such as shape memory alloys [7], pneumatics [12] and magnetism [36].

In this research, we focus on the precise control of liquid metal, specifically the locomotion and vibration of droplets through electrode switching. Gallium-based liquid metal alloys, which can be liquid at room temperature (~20 °C), are a compelling option when designing novel shape-changing interfaces. In their liquid state, these materials retain desirable liquid properties (e.g., high deformation), whilst also retaining enough density to provide tactile sensation.

Despite the possibilities of using liquid metal as a visio-tactile display, this has only so far been explored through use in widgets [32], to create visual spectacles [52] and to create weight change interfaces [35]. Previous developments of tactile feedback with liquid metal are constrained in their ability to freely move the fluid in any direction. Instead, the liquid metal is typically fixed in physical channels, spreading from anode to cathode, creating directional force through the displacement of the fluid within the confining channel.

In contrast to previous work, Tangible Drops provides tactile sensation through the locomotion and vibration of liquid metal droplets, allowing for them to form tangible actuators which may be vectored and positioned on a 2D plane. This approach has the benefit of freedom of movement and pixel-like control of a variety of tactile sensations, allowing highly configurable control of dynamic tactile sensations to convey directional, positional and intensity information. We are, therefore, able to demonstrate the first combination of location and vibration of a material to provide tactile information. The key contributions of this paper are:

- A method for programmable 2D planar control of liquid metal drops through the use of an electrode array;
- A number of techniques to create a variety of visual and tactile effects, e.g., through locomotion and vibration;
- A focused investigation of the efficacy of the tactile effects created, with vision to understand the opportunities and challenges of tactile liquid metal displays.

Our work, then, for the first time presents tactile feedback via locomotion and vibration of a liquid drop on a flat surface, including an empirical study for exploring the possibility of using such actuated material blobs for eyes-free interaction.

## RELATED WORK

Below, we review techniques that can be used for both visual and haptic/tactile feedback, considering firstly non-fluidic approaches, and then those more directly related to our method.

### Non-Fluidic Viso-Tactile Interfaces

There are a large number of example prototypes that use mechanical accuation, elastic material manipulations or electrical stimulation to provide visio-tactile interfaces.

For instance, devices using an array of mechanical actuators may be employed as widgets for tangible interactions (Sublimate [30], Emergeables [39], Haptic Edge Display [18]), and visual interactions (Emerge [49], KineReels [50]). In addition, haptic feedback may be provided through creating a surface deformation (FEELEX [17], Relief [31], Shade Pixel [27], Kintetic Tiles [28], ShapeClip [11], Materiable [33]) and/or locomotion of objects (inFORM [10]).

In contrast to actuated mechanical devices, elastic material based interfaces can provide interactive information display via natural haptic feedback. For instance, an inflatable latex screen with media projection may provide haptic feedback on a visual display [47]. Further, TableHop provides vibro-tactile feedback on a fabric display using an array of transparent electrodes for electrostatic actuation [42]. Previous work has also looked at pnuematically actuated physical buttons on a visual display, providing low-attention and vision-free interactions through their intuitive tactile clues [12, 40].

Electrical actuation can also provide tactile feedback on a touchscreen display. Electrovibration with a transparent electrodes on a display can provide texture (TeslaTouch [1]) and geometry information [41]. Such systems require users to move their fingers to feel the tactile sensation. Skeletouch provides electro-tactile sensations via direct electrical stimulation using an array of transparent pads on an LCD touchscreen [21], or at the back of the screen [26]. Finally, Sparkle uses touchable electric arcs from a transparent electrodes to provide tactile feedback while hovering on a display [45]. These devices provide tactile feedback on a stationary finger.

### Fluidic Interfaces

Providing convincing tactile feedback for different scenarios using a material or technique is a major open challenge. Actuated fluidic interfaces offer a potential way forward as their highly deformable nature make them strong candidates for shape-changing interfaces. To this end, haptic displays using smart liquids have been proposed [60]. Programmable blobs [57, 56] (pBlob), Programmable Liquid Matter [52] (PLM) and LIME [32] are closely related to the present system, Tangible Drops. We present the unique visio-tactile capabilities of an actuated shape display using a fluid material with Tangible Drops that are different from these previous works, as we detail below.

PBlob [57] is a visual system which uses an array of electromagnets to manipulate a custom ferromagnetic fluid, and presents information visually via translation, deformation, unification and division operations. The ferrous gel in pBlob is relatively viscous and not suitable for vibrotactile feedback. The power consumption is high, i.e., 6 W per node. The resolution is low, and it is difficult to scale using electromagnets; furthermore it is not portable due to its heavy magnetic system. PLM [52] is also a visual system which uses an array of electrodes to make connected patterns by spreading a large liquid metal blob. The tactile capabilities of pBlob and PLM, are not reported. Our studies, presented later, indicate that they would likely not provide sufficient tactile or haptic feedback due to relatively low magnitude of static feedback force.

LIME [32] used liquid metal, like Tangible Drops, and presented *widgets* for non-rigid interaction. This work exploited the reversible deformation of liquid metal in contact with a positive electrode in closed channels and small cells, which limited its visual and tactile capabilities. PLM [52] used the same principle to spread liquid metal. In LIME, the visual effects were limited to hidden/revealed or checked/unchecked states, and the size was limited to small widgets. The tactile sensation was limited to the point of contact. The tactile feedback was also weak due static force for the two deformed states, i.e., spherical and flat shapes. In this paper we exploit the hopping of liquid metal drops to-from and in-between positive and negative electrodes on a flat surface to create further general purpose visual and tactile effects such as an abstract visual display and strong vibrotactile feedback with direction information.

### Digital Microfluidic Systems

The design of Tangible Drops is inspired by the design of microfluidic (DMF) systems which control individual drops above an open array of planar electrodes to move, merge, mix, split, and dispense-from-reservoir [34, 6, 5]. DMF handles *water*-based solution drops which have dielectric properties. The drops are controlled by switching the low-voltage applied to the electrodes. The movement is caused by electrowetting on dielectric (EWOD). It relies on electrostatic force and energy from the charges accumulated at the dielectric layer along the contact line. The open electrode arrays are covered with a dielectric layer and further coated with a hydrophobic insulator on top. Two parallel electrode plates with the drop squeezed in-between are required to split and dispense. Due to metallic properties, the liquid metal drops in Tangible Drops could not be moved with a dielectric layer on top of the electrodes.

### Liquid Metal Applications

The HCI community has recently begun developing interfaces that incorporate liquid metals. Niiyama et al. [35] used liquid metal to alter the shape and weight of a device through pumping Ga-In-Tin eutectic with a bi-directional pump. As previously noted, Lu et al. [32] utilised liquid metal (EGaIn) drops which change their spherical shape to a flat shape when a voltage is applied, and made widget cells offering visual and tactile effects. Tangible Drops presents a *general purpose* visual and tactile display for the first time using liquid metal.

The material science community has explored many viable applications of liquid metal that are interesting to the HCI community. Ladd et al. [29] 3D printed stable free standing liquid metal (EGaIn) structures such as arches, towers and tree etc. at room temperature in air with a syringe needle. Hu et al. [14] made stable planar structures such as line, triangle, rectangle and ring on a graphite substrate in NaOH solution. Jeong et al. [20] made a wearable flexible RFID tag. Boley et al. [4] made a glove with an array of inkjet printed liquid metal strain gauge sensors, which could be used for information input or gesture sensing. A range of applications given in a review of liquid metal enabled flexible electronic [59], and microfluidics [25] are of interest.

Liquid metal offers many opportunities for creating user interfaces. Existing work is focused on liquid metal locomotion constrained to channels. We are interested in full 2D planar motion control and vibration control to make visio-tactile liquid metal user interfaces.

### Liquid Metal Control Techniques

Tangible Drops manipulates liquid metal by electrical control of surface tension between the liquid metal and the base. Eaker and Dickey [9] review such techniques, i.e., electrocapillarity, continuous electrowetting, electrowetting-on-dielectric and electrochemistry. All techniques except continuous electrowetting require the liquid metal drop to be in contact or on top of an electrode. LIME used the electrochemistry technique [32]. Khan et al. [24] and Zhang et al. [63] showed the electrochemistry technique with liquid metal drop *spreading* on the anode, and spreading in a capillary channel towards the cathode with anode always in contact with the drop.

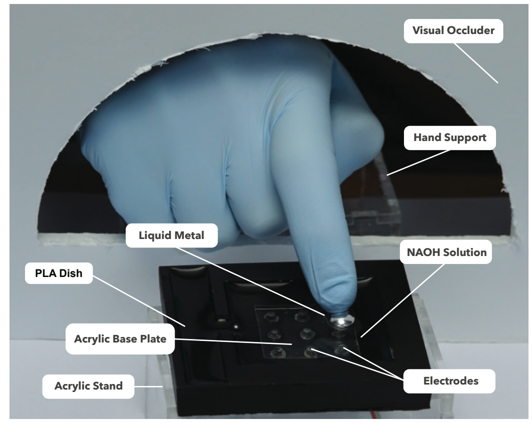


**Figure 2. Our implementation uses a 3D printed PLA dish with an acrylic base plate. 2.4 mm diameter steel electrodes were embedded at 11 mm intervals and driven by a switching circuit.**

Beni et al. [2] introduced the continuous electrowetting (CEW) effect and demonstrated *locomotion* of liquid metal slugs in capillaries (in cathode-to-anode direction without the electrodes in-contact with the slug). The CEW effect makes the liquid slug flow towards regions of lower surface tension in order to wet it more. It relies on a surface tension gradient induced by a voltage gradient tangential to the liquid-solid interface. CEW has been used in microfluidics to bend and squeeze through micro channels [62]. Sheng et al. [43] moved a liquid metal droplet in a water *channel* on a horizontal plastic plate using two jumper wire leads, however, they do not show 2D planar locomotion. Tangible drops employs this technique, and for the first time shows manipulation of liquid metal drops on an open surface and its vibration using an array of electrodes. Finally, Tiest [51] studied the tactile perception of viscosity and wetness properties of liquid metal using psychophysical characterization in terms of magnitude estimation experiments and discrimination experiments.

## TANGIBLE DROPS

We describe Tangible Drops via the implementation shown in Figs. 2 and 3. In general, an implementation will have a custom designed flat dish to hold the liquid metal drops, an electrolyte to submerge the drops, a base plate that is not wet by the liquid metal, and an optional reservoir at a custom location to dispense or store the liquid metal. The visio-tactile display area is covered by a 2D array of electrodes embedded in the surface. The electrodes are also laid in the feeding channel from the reservoir. In Fig. 2, we show a square display with 3×3 electrode array, a reservoir on one side with 3 electrodes in the feeding channel.

Tangible Drops manipulates the position, locomotion and vibration of liquid metal drops by modulating and switching the

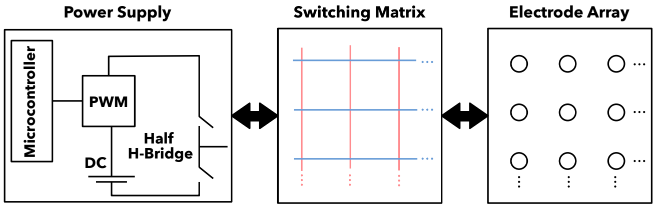


**Figure 3. A driving circuit with a DC PWM power supply, H-bridge switch for bidirectional control and a switching matrix for individual electrode selection is shown.**

polarities of voltage applied to individual electrodes. In Fig. 3, the electrodes are connected to an array of H-bridge drivers to switch the voltage polarities from positive to ground or negative voltage for discrete control. A pulse width modulation (PWM) scheme could be employed for continuous control. A passive, active or segment matrix could be used for selecting individual electrodes. In our implementation we used a DC power supply, with 10 ohms resistors at the outputs of the h-bridge circuit (L293D) to limit the current. The current was also limited at the power supply for safe operation. An Ardunio Mega was used with a PC for PWM and electrode selection.

Systems such as Tangible Drops prefer room temperature liquid metals such as gallium-based eutectic alloy, to allow operation without temperature control. The GaInSn eutectic alloy (made of 67% Ga, 20.5% In, and 12.5% Sn by volume) has a melting point of 10.35°C. The (EGaIn) GaIn25 eutectic alloy (made of 75% Ga and 25% In by volume) has a melting temperature of 15.7°C. In addition, these are generally chemically stable and do not react with water at around room temperature. Previous studies have proven that such an alloy is safe for humans under normal circumstances. We used EGaIn which has a density of 6.25 times the density of water, and could provide effective tactile feedback via locomotion and vibration.

A suitable nonmetallic material could be chosen as the base plate such that the liquid metal does not wet it. Generally, liquid metal wets most nonmetallic surfaces easily after rubbing over them, creating a thin layer of metal oxide. A glass or acrylic substrate can be used as the base plate with careful handling of the liquid metal drops. We utilised laser-cut acrylic as our base plate.

Likewise, a suitable metal electrode should be chosen such that the liquid metal does not wet, react or corrode it. Liquid metal can react and dissolve many metals, and also corrode most metals (Gallium is corrosive to all metals except tungsten and tantalum). Metals with higher difficulty of solderability are ideal for such systems. Liquid metal does not attack carbon/graphite rods, but they delaminate during electrolysis with the higher voltages required to reliably electrode-hop (as shown later in this section). Liquid metal wets most metals after the native oxide layer is removed. By applying an oxidizing potential the electrodes can be protected.

### Liquid Metal Actuation

The operation of Tangible Drops is based on the continuous electrowetting (CEW) principle (see Fig.4), described earlier. The liquid metal droplet moves towards the anode (+ve voltage) away from the cathode (GND/-ve voltage). The voltage

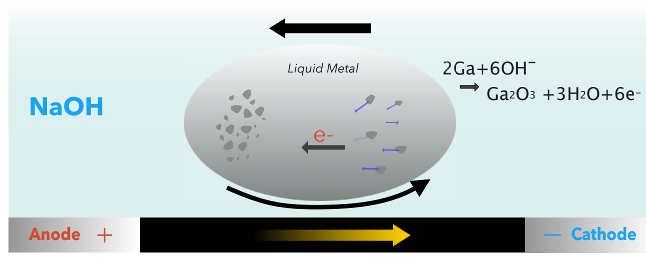


**Figure 4. Tangible Drops works following the continuous electrowetting principle. The voltage gradient between positive (anode) and negative/ground (cathode) electrodes creates a gradient in the surface-tension between the liquid metal drop and base. The drop moves towards the lower surface-tension area, i.e., towards the anode in order to wet it. Due to electrolysis, the oxide formation aids the reduction in surface tension, and electron creation aids the movement towards the anode.**

gradient creates an inter-facial tension gradient between the liquid metal and the base plate due to the gradient in accumulated charge density in the drop at the interface. The drop moves towards the lower surface-tension area, i.e., towards the anode in order to wet it. Due to electrolysis, the surface oxide formation aids the reduction in surface tension, and electron creation aids the movement towards the anode on the open flat surface without being constrained to a physical channel. Tangible Drops moves the liquid metal droplet from electrode to electrode by switching their polarities. By switching the position of the anode, the liquid metal droplet is manipulated bidirectionally over the electrode array.

CEW requires an electrolytic solution layer between the liquid metal and the base plate. Acidic and alkaline solutions could be used. Hydrochloric and sulphuric acids have been used as CEW are demonstrated in closed micro channels. Sodium hydroxide generates oxygen and hydrogen gases during electrolysis, and is therefore suitable for Tangible Drops interfaces due to its relatively low risk.

## CAPABILITIES AND TECHNICAL EVALUATION

Now we have outlined the design of Tangible Drops, we proceed to investigate its operation capabilities and describe our process of evaluating the system from a technical perspective.

### Placement and Vectoring

Tangible Drops can place, vector and vibrate liquid metal drops using the electrode switching technique. The drop is placed at an electrode by setting it as anode and the rest of the electrodes around it as cathode to direct the electric field towards it (see Fig, 5(left)). The drop is vectored by changing the placement location (see Fig, 5(right)). The drop moves quickly to the new location. By vectoring the drop quickly between the electrodes it is possible to stably place it between electrodes. If the drop stays at an anode for long enough to come in contact and go through electrochamical oxidation then it spreads at the electrode. The bubbles created during electrolysis can limit spreading. Higher concentration of the electrolytic solution and higher voltage aided bubble formation.

### Voltage Requirements

The minimum voltage required to vector the droplets is dependent on their size, shape, applied voltage, separation between

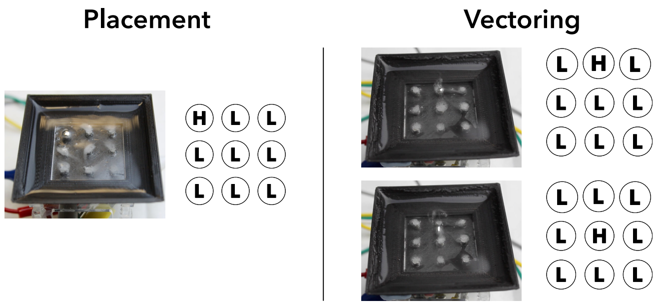


**Figure 5. Placement and vectoring of liquid metal: here we see our system for electrode switching, where the gallium is drawn towards the high (H) electrode, where all others are switched off to low (L).**

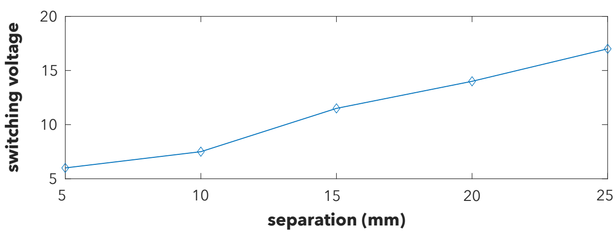


**Figure 6. The minimum voltage required to switch a 3 mm EGaIn droplet between steel electrodes 10 mm apart in 2M NaOH solution.**

the electrodes and ionic concentration. The results of an experiment to find the successful switching voltage at various electrodes separation with 3 mm diameter drop are shown in Figure 6. The electrode separation was set to 10 mm and the switching voltage was fixed at 10 V for our prototype using the 3×3 grid and 2.4 mm diameter steel electrodes.

The average speed of the drop is approximately six times its body length per second [43]. The speed could be controlled by modulating the magnitude of the applied voltage, or by using pulse width modulation for a given peak voltage. The speed increase might result in the drop overshooting the target location. Without closed-loop control of the voltage, i.e., without monitoring the position and speed of the drop, the speed of operation is limited to the average speed with limited overshoot, as mentioned above. We reduced the switching time period to speed up the liquid metal drop. Fig. 1(a) shows the visual display demonstrator animating the letter “S” at 500 *ms* switching time. With 10 mm separation of the electrodes, the maximum useful speed of the implementation is 20 mm per second with a 3 mm diameter drop and allowing moderate overshoot. Wang et al. [58] provide an experimental model of the effects of the drop size, the concentration of the electrolyte solution and the applied electric field on the movement behavior of the drops in micro channels. However, Tangible Drops uses an open electrode array that is not reported, here, as its analysis and modelling is a topic for future work.

### Merging and Splitting

The operation of the liquid metal reservoir of Tangible Drops was evaluated using the prototype shown in Fig. 7. We employed CEW to move the electrode from the display area to the reservoir, which is easily achieved. However, the splitting using CEW has low success rate unless the drop sits at the dead

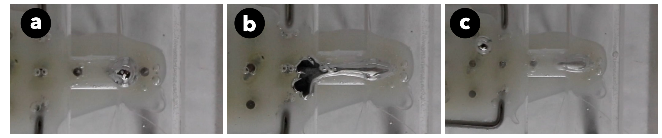


**Figure 7. (a) A large spherical drop in the reservoir (on the right). (b) The drop spreads into the display area (on the left) from the reservoir by setting the electrodes in the feeding channel as anodes and the electrode in the display as cathode. (c) When the polarities are reversed the liquid metal splits and enters the display area. A small spherical drop remained in the reservoir.**

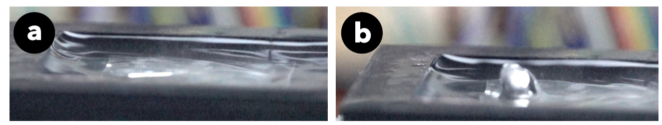


**Figure 8. Oscillation on a single electrode: (a) shows the droplet in its flattened state, and 60 ms later (b) shows it in its actuated state.**

center between two electrodes. Closed-loop monitoring could be useful for splitting using CEW. We employed a combination of electrochemical spreading [32] and CEW to achieve splitting from the reservoir and feeding drops to the display on demand. First the electrodes in the feeding channel were set as anodes and the closest electrode in the display was set as cathode for the liquid metal to spread into the display area. Then the polarities were reversed for the liquid metal to split and move to the electrode in the display area which is now set as anode. The size and number of drops is dependent on the amount of liquid metal spreading and the number of branches, which is decided by the number and configuration of electrode polarities.

### Oscillation

The vibration of liquid metal drops was evaluated using the electrochemistry (*on-electrode oscillation*) and CEW (*between-electrode oscillation*) techniques (see Fig. 8). For on-electrode oscillation, we switched the polarity of the electrode at a given frequency, and for between-electrode oscillation we switched the polarities of the two electrodes with respect to each other at a given frequency. All other electrodes were set as cathodes. The drop vibration was observed using a high-speed camera at 250 Hz. The on-electrode vibration was vertical (z-axis) with the drop jumping out of the solution and falling down to a flat shape. The between-electrode vibration had both lateral (x and y axes) and vertical components. The vibration frequency of the drop was independent of the driving frequency. The number of vibrations depended on the duty cycle of the driving voltage. The frequency of the vibration depend on the drop size. Both vibration modes could be combined with locomotion between the electrodes.

The current drawn by the 3×3 grid prototype from the DC power supply was 400 mA at 10 V. The power consumed by the prototype, including the driving circuit and excluding the Arduino power consumption, was 4 W. The resistance at each electrode is 225 ohms. Subtracting the 10 ohms external resistor, the electrolytic resistance at each electrode was 215 ohms. Previous work has found that target size of 9.2 mm and 9.6 mm for discrete and serial tasks respectively should be sufficiently large for one-handed thumb use on touchscreen-based


**Figure 9. Vibration of liquid metal drop between two electrodes: by electrode switching between the top central electrodes in the figure at 60 ms, one can see,over about 120 ms, the droplet being pulled by each electrode, from a laterally stretched blob, to a spheroid shape and finally to a longitudinally stretched blob.**

handhelds without degrading performance and preference [37]. User interface guidelines for developers from Apple, Windows and Google recommend minimum touch target size of 7 mm for the index finger. We fixed the separation between the electrodes at 11 mm following the target size guideline for touch from Microsoft [23] and chose a drop of 8 mm diameter for the tactile feedback use cases.

## EVALUATION OF TACTILE FEEDBACK METHODS

So far in this paper we have described a number of techniques to provide tactile feedback to users. We have also described[1] our approach which uses drops of liquid metal moving and vibrating between electrodes. To understand the capabilities of our system as a tactile display, we conducted a user evaluation with the following research questions:

**RQ1:** Does locomotion make it easier to feel the droplet?

**RQ2:** Can users perceive changing speeds of:

- **RQ2a:** locomotion; and,
- **RQ2b:** vibration?

**RQ3:** Can users determine the direction of travel of a droplet?

**RQ4:** What is the qualitative user experience of using such a method for tactile feedback?

### Participants and Study Environment

We recruited 12 participants (7F, 5M, 21–53 years, avg. = 34.5 (SD = 9.76)) from a university staff population, all of whom were unrelated to this research. Participation was incentivised at £5 per half hour (rounded up to the nearest half hour), with experiments typically taking between 1 and 1.5 hours). The only screening characteristic in our recruitment process was that all participants must have normal perception in their fingers. During a pre-study questionnaire, all participants strongly agreed that they were regular smartphone users, and either strongly agreed (5) or agreed (7) that they had good touch perception in their fingers. Ten of our participants were right-hand dominant, and two were left hand dominant.

### Study Procedure

The study was run in a controlled lab environment with little external influence. Two experimenters (hereby referred to as Experimenter 1 and Experimenter 2) ran the study with each participant. The study began with a safety briefing to ensure that the participants knew the potential dangers of the substances they would be interacting with (see later in the paper for a discussion of the safety aspects of the design). The participants wore a lab coat to protect them (and their clothing) in event of an spillage. An eye-wash station and a wash-basin were also available nearby. Each participant wore a standard powder-free nitrile glove, choosing the smallest size available to fit their hand, ensuring close contact and minimal interference. There were no spillages or accidents during the study.

After an IRB-approved ethics procedure, we gained the participants' consent and demographic information. A 2-point discrimination test was then conducted to ensure that they had minimum typical perception of tactile sensations on their fingers. A person with 'normal' tactile perception on their fingers should be able to perceive a difference in one or two points with 8 mm separation [3]. We chose this value for our test and used a custom 3D printed discriminator to conduct the test with a standard methodology adopted from Crosby et al. [8]. All participants were given 10 random vertical vs. horizontal and 1 vs. 2 point trials to say whether there were 1 or 2 points touching their fingers. All participants, except one having particularly calloused skin, scored 100%. A replacement participant with normal tactile perception was recruited.

The participant was then seated opposite the Tangible Drops device, with their hand on a rest and their vision occluded (as shown previously in Fig. 2). To answer the research questions laid out in the previous sub-section, we conducted a study with seven parts. For each part, Experimenter 1 ran the required code and randomly generated procedures. Experimenter 2 ensured that the participants' fingers were consistently placed in the correct place in accordance with the experimental plan. This was done with verbal directional instructions and with an acrylic finger guide.

All parts were automated by an Arduino script, in which each part was started by entering the desired number to the interface and then running each randomly generated condition six times. Participants were free to rest until they were ready for the next condition. This was generally less than 30 s. Experimenter 1 also asked the relevant experimental questions and noted down the participants' responses in a database. This process was repeated for each test until completion. Finally, both experimenters interviewed the participant and captured the audio. We now describe each test administered to the participants, along with the associated research goals in terms of what we wanted to understand. A graphical outline of the stimuli used in each test can be seen in Fig. 10.

#### *Part 1: Perception of Static Liquid Metal*

Towards answering RQ1, in Part 1 we aimed understand if users could effectively determine the presence of liquid metal while static. We conducted a study in which Experimenter 2 randomly placed liquid metal underneath the participant's finger at a fixed point with all electrodes switched off. We asked the participant to rate their perception of whether they believed there was something under their finger on a 1–5 Likert-like scale by asking them to state their agreement with the statement "I believe that there is something under my finger", '5' being "Strongly Agree", '1' being "Strongly Disagree".

#### *Part 2: Perception of Locomotive Liquid Metal*

To answer RQ1, and understand participants' perception of locomotion, Part 2 of the study involved the movement of liquid

[1]See supporting video for details.

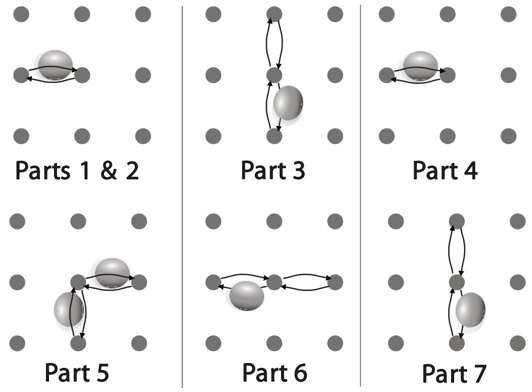


**Figure 10. The motion of the liquid metal that was used for each test. The participants were directed to place their fingers over the middle electrode for each part of the study, except parts 1, 2 and 4. For these tests, they were asked to place their fingers between the relevant electrodes.**

metal as the independent variable. For each trial, the Arduino script randomly selected whether the droplet was moving or not. If the droplet was chosen to not move, no voltage was applied and the liquid metal remained static. Otherwise, in the 'moving' condition, the liquid metal was repeatedly vectored between two electrodes, with an interval of 700 ms and without any carrier frequency (i.e., no vibration of the droplet). The participant was guided to place their finger at the same point (coinciding with the droplet) by Experimenter 2 regardless of experimental condition. We asked the same question here as we did in the Part 1, relating to whether the participant could feel something under their finger.

*Part 3: Perception of Locomotion Speed*

To understand if users can determine changes in speed of *locomotion* (RQ2a), we conducted Part 3 in which the system moved the blob across three vertical electrodes at a given speed, then changed it to one of two pre-defined speeds randomly (faster, or slower). The initial speed set was 500 ms, at which point the participant was asked to place their index finger on the middle electrode to gain a sense of its speed. Once the participant felt that they had an impression of the current speed of the blob, the microprocessor then randomly increased or decreased this by 200 ms depending on the speed allocation. We asked each participant to report whether it got faster, or slower by asking them to state their agreement with the statement: "*Do you believe the movement got slower, or faster?*", where "Definitely Faster" is 5, "Definitely Slower" is 1, 3 being unsure of either. After each trial, the speed was returned to regular, which allowed participants to re-calibrate.

*Part 4: Perception of Vibration Speed*

To understand if users can determine changes in speed of *vibration* (RQ2b), in Part 4 we oscillated the droplet between two horizontal electrodes at a set frequency, then, changed it to one of two pre-defined speeds randomly (faster or slower). We set the initial vibration frequency at 60 ms. The participant was guided to place their finger at a fixed position on the vibrating droplet, between the two electrodes. Once satisfied they could feel the vibration, and accustomed to its rate, the speed at which the droplet vibrated was randomly increased or decreased by the experimental script run by the microprocessor. We asked the same question to the user regarding speed as in Part 3, returning to the original speed after each trial to allow the user to calibrate.

*Part 5: Differentiating Vertical and Horizontal Movement*

Towards answering if users can determine the direction of travel of a droplet (RQ3), Part 5 randomly selected if a droplet was to move to the electrode directly above it and back, or to the electrode directly to the left of it and back. Both conditions were run at 700 ms and with a vibration frequency of 40 ms. The participant was asked to place their finger on the origin electrode. Then, once the droplet was moving they were asked to report in their own time which direction they believed it was travelling in – horizontal or vertical for each trial.

*Part 6: Differentiating between Left & Right*

To further refine the answer of RQ3, Part 6 was to understand if users could determine the droplet in terms of absolute horizontal direction. The participants were first asked to place their finger between three horizontal electrodes. The drop was then moved back and forth laterally. We kept the blob at the sides for 1400 ms and then moved between the central electrode at 700 ms, allowing the participant enough time to announce the direction of travel they experiences – either "left" or "right". Both experiment coordinators then agreed upon the actual direction of travel for comparison. In times of experimenter disagreement, no direction was reported. We conducted this until the user reported six directions.

*Part 7: Differentiating Between Up & Down*

Towards gathering more data for RQ3, a similar methodology as the previous part of the experiment was applied to Part 7 to understand if users can differentiate between up and down movement of the liquid metal. We moved the blob as before, except this time along three vertical electrodes. Again, the participant noted the direction of travel, and both experiment coordinators noted whether this was correctly reported.

*Interview*

After all seven parts were completed, we asked the user to reflect on the experience as a whole through a semi-structured interview that considered subjective perceptions of the liquid metal in the static, vibration and locomotive states. Participants were asked to describe the sensations they felt.

## Study Results

We now describe the results from each of the studies in turn to get a better understanding of the efficacy of the techniques implemented for our liquid metal display. To test statistical significance, we conducted Kruskal-Wallis tests on the ranked data and $\chi^2$ tests for the categorical data.

*Results: Part 1 – Perception of Static Liquid Metal*

To determine if there was an effect for participants' perception of liquid metal when static, we compared the results when the material was present and not present. A mean rank of 30.25 was reported when the liquid metal was not present and 40.48 when present. There was a significant effect when comparing the conditions: $\chi^2$ (1) = 4.47, p = 0.035, with a small effect size of $r$ = 0.062, suggesting that only around 6% of the variation in conditions was related to the liquid metal's presence.

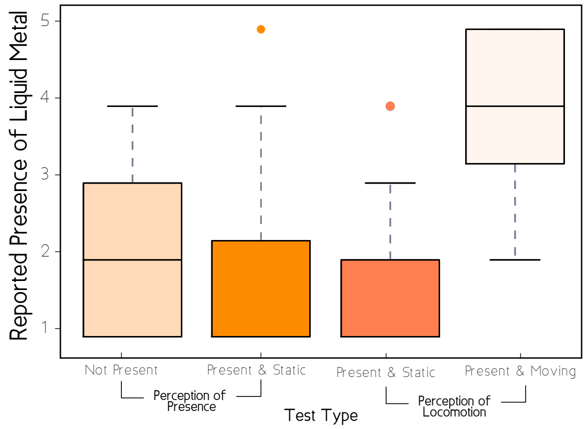


**Figure 11. Participants' reported presence of liquid metal. A score of '5' indicates strong agreement that the liquid metal was beneath the finger, and a score of 1 indicates the inverse. Reported values increase dramatically when the droplet begins moving back and forth between electrodes.**

| | | Left | Right | Correct | Average |
|---|---|---|---|---|---|
| **Left** | *Observed* | 31/40 | 9/40 | 77.5% | 84.05% |
| | *Expected* | 18.9 | 21.1 | | |
| **Right** | *Observed* | 3/32 | 29/32 | 90.6% | |
| | *Expected* | 15.1 | 16.9 | | |

**Table 1. Observed vs. expected results for the Left/Right condition.**

*Results: Part 2 – Perception of Locomotive Liquid Metal*

To understand the effect of introducing locomotion to liquid metal, we compared the data gathered when the liquid metal was moving and when it was static. When static, the mean rank was 19.72 and when moving it was significantly higher: 51.51, with $\chi^2$ (1) = 43.92, p < 0.001, and a large effect size $r$ = 0.62.

*Results: Part 3 – Perception of Locomotion Speed*

Participants also could effectively determine if the speed of the droplet had increased or decreased. They ranked the speed of the fast condition significantly higher than that of the slow condition once moved from the original speed (faster: 51.27; slower: 22.53). The difference between the two conditions was significant: $\chi^2$ (1) = 35.81, p < 0.001, with a large effect size of $r$ = 0.50.

*Results: Part 4 – Perception of Vibration Speed*

When the vibration speed was changed from 'normal' to 'slow' there was a reported mean rank speed of 24.06, which increased to 48.27 when the speed was 'fast'. Similarly to movement speed, there was a significant difference – $\chi^2(1)$ = 25.50, p < 0.001, with a medium effect size of 0.39. Fig. 12 describes the overall ranking of the participants with regards to the perception of changing locomotive and vibratory speed.

*Results: Part 5 – Differentiating Between Vertical & Horizontal*

To find out if users were able to accurately differentiate between longitudinal and lateral movement we conducted a compared the observed data compared to what one would expect by chance. Participants were able to correctly determine horizontal movement 78% of the time and vertical movement 79% of the time, which is a statistically significant result: $\chi^2$ of 24.40, p < 0.001 and a (large) effect size ($\phi$) of 0.58.

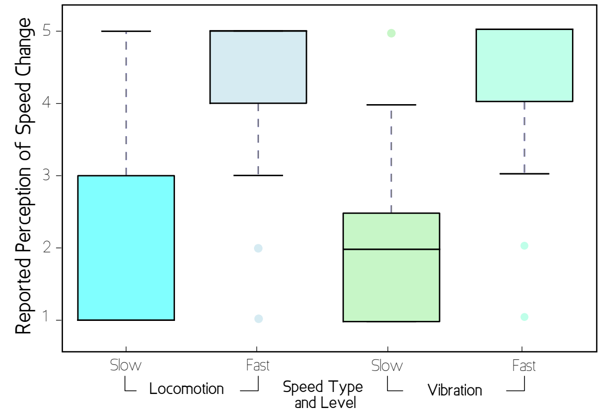


**Figure 12. Effect of changing the speed of locomotion and vibration of a droplet to either slow, or fast. Participants were able to differentiate between whether the droplet had sped up, or slowed down, for both cases.**

| | | Down | Up | Correct | Average |
|---|---|---|---|---|---|
| **Down** | *Observed* | 23/31 | 8/31 | 74.2% | 84.65% |
| | *Expected* | 10.8 | 20.2 | | |
| **Up** | *Observed* | 2/41 | 39/41 | 95.1% | |
| | *Expected* | 14.2 | 26.8 | | |

**Table 2. Observed vs. expected results for the Up/Down condition.**

*Results: Part 6 – Differentiating Between Left & Right*

To understand further the ability of the participants' perception of locomotion, analysis was conducted with regards to the participants' ability to correctly ascertain the direction of travel when oscillating the droplet laterally, the results of which are described in Table 1. Participants were found to be significantly more accurate than chance when determining the direction of the droplet: $\chi^2$ = 33.11, p < 0.001, with a large effect size ($\phi$ = 0.67).

*Results: Part 7 – Differentiating Between Up and Down*

The results to compare the participants' perceived direction for which way the droplet was travelling up and down can be seen in Table 2. Analysis shows a significant effect: $\chi^2$ = 37.42, p < 0.001, with a large effect size ($\phi$ = 0.72).

*Interview*

For the post-study interview data we captured a wealth of audio recordings from participants, which were analyzed post-study with respect to each question asked. With regards to participants' perception of static liquid metal, many noted issues with feeling the substance, and often noted that they either were not totally sure they were touching some liquid metal or did not feel anything at all. In total, only 5 (approx. 42%) participants described feeling the liquid metal. P10, who did feel something in the static condition, described it as feeling as "*a bit more density*". P11 noted the uncontrolled, transient nature of the droplet: "*[...] like when you have a bit of eggshell in an egg white [...] always moving out of your way [when you try to touch it]*".

With locomotion imparted to the droplet via electrode switching, all participants noted experiencing some sensation under the finger. The locomotion of the droplet was described through three main metaphors. Some described the sensation as "*bubble-like*" (P1, P6, P7), others as a "*shock*" (P3, P6, P7) and many as a "*pulse*" (P4, P5, P8, P11, P12). The participants noted that these effects were exacerbated strongly by the vibration. Participants' comments suggested that some could feel it continuously moving along their finger, and others as occasional nudging.

Some participants noted not always feeling the movement get faster when vibrating. One noted that sometimes it felt like the droplet stopped moving: "*the high frequency just felt continuous for me*" (P10). Others felt that the vibration had a very strong effect at all speeds, for example P7, who found that "*the vibration changing speed was very obvious*". One participant found the vibration particularly strong, describing it as "*like when you drill a wall and have your other hand on it*". This participant also noted a lasting effect: "*now [after the experiment] my finger feels tingly, like when you have pins and needles*".

With regards to the perceived qualities of the material, participants' analogies mostly related to natural processes such as heartbeats, animal movement and bubbles in water. P8 thought that the cognitive process in determining the speed of the droplet was analogous to trying to detect a pulse: "*it's a bit like you are doing first aid – you're trying to feel the pulse and switch your mind off from what's going on around you*". A similar link was made by P5, with the comment "*it felt like a heart racing, like when my son has done some exercise*". P5 also described the sensation of the liquid metal travelling under their finger as "*like a frog*", alluding to the pulsing motion of a frog's throat sac.

Participants generally did not experience any kind of 'heat' sensation, or feel the relative coldness of the metal, but generally described some form of mechanical process. However, from touching the droplet, participants generally did not note a feeling of a physical object or a displacement of mass *per se*, but more of a sensation, or vibration: "*it feels more like a vibration than an object*" (P8); "*you could feel it arriving and departing, but not actually underneath your finger*" (P11).

### Discussion of Study Results

The findings indicate the proposed techniques are able to provide continuous eyes-free tactile feedback for users. Regarding RQ1, though static liquid metal is perceived by users better than chance, there is a negligible effect, suggesting little reliability of a tactile material while static. It is possible that this result would change as the temperature of the environment changes (our study environment was room-temperature). As the viscosity of the substance varies with temperature, this would change the relative difference between the liquid metal substance and the electrolyte solution. Moreover, varying the temperature may have also affected the relative difference in percieved wetness. Bergmann Tiest [51] outlines a number of studies which suggest that wetness is affected by temperature. A colder environment may have allowed the highly conductive thermal properties of the liquid metal to become more apparent, creating a larger heat differential and a larger perceivable difference between the liquid metal and the electrolyte, resulting in easier perception.

With the introduction of locomotion all participants were able to detect tactile sensations with much higher proficiency. This suggests that (in reference to RQ1) locomotion allows the participants to feel the droplet more effectively.

Relating to RQ2a, participants could determine if the droplet had sped up or slowed down significantly more accurately than by simple chance. The large effect size suggests that this was done so with relative reliability. Interviews, supported by the range in the accuracy of the data between participants, suggest the variability was down to the different sensitivity of the individual's fingers, which is noted as a clear factor in other studies of tactile perception [22, 44]. This inter-participant variability was also seen in RQ2b. With regards to participants' ability to perceive changing vibration, it was clear that some participants were much more able to perceive the vibration speed changing. P8, for example, who described it as strong as a vibrating wall from drilling and experienced a tingling sensation in their fingers after the experiment, also was able to determine the change of locomotion speed, vibration speed and all directional tests with 100% accuracy.

Regarding RQ3, it was evident that participants could not only determine between both vertical vs horizontal, but also the specific directional information. Participants performed better when the droplet was going right (as opposed to left) and up (as opposed to down). A potential explanation for this is that the participants were better at perceiving the droplet moving away from them; stroking the inside, or underneath of finger first. Further, when travelling upwards, the shallower contact angle may have contributed to more skin contact and therefore more chance of experiencing a sensation more accurately.

With regards to the qualitative data captured in the interview (relating to R4) we found that participants often referred to the liquid metal's motion as an '*alive*' material. This quality is likely due to the droplet's somewhat erratic shape change and motion as it moves and vibrates. Such naturalistic interaction is likely conveyed by the droplets' duality of controlled motion on the macro-scale and chaotic variability on the micro-scale, suggesting notions of a living organism. This implies that the methods employed in Tangible Drops may provide the potential to foster more naturalistic interactions with technology (see organic user interfaces [13]). Organic interfaces can trigger emotional connections and a sense of empathy with interfaces [46], and may provide a humanizing sense to our interactions, in turn making such technologies more accessible to broader audiences (c.f., Hwang et al's interactive plant [15]).

## LIMITATIONS AND FUTURE WORK

Though this paper outlines a number of novel interactions, which have been shown to be effective at conveying eyes-free feedback to users, we are still limited by a number of constraining factors.

We now describe our technique's limitations and provide some future direction with a view to overcome these constraints. We then, through the lens of our *current* techniques, outline potential future use cases. We do so with a vision to encourage others to replicate and augment our techniques with these and further use cases in mind.

## Addressing Limitations

One main limitation of Tangible Drops is that the locomotion requires a flat horizontal surface to work. CEW can be effective on surfaces with limited slope [2]. In [14], liquid metal drop locomotion using $10V$ voltage on a graphite surface with a slope of 10° is demonstrated, and the possibility of locomotion on higher slopes using higher voltages is discussed.

Another limitation of Tangible Drops is touch-ability as it requires an electrolytic solution to work. We used NaOH, which can cause skin irritation. To avoid this, the participants used nitrile gloves. We experimented with providing a protective barrier (e.g., cling film) similar to Lu et al. [32]. However, NaOH often made the film slippery and difficult to fix. It required venting of the gases from electrolysis, and could not be operated reliably for sustained usage. Note that the $H_2$ and $O_2$ gases from electrolysis of NaOH could cause minor throat irritation to users with respiratory problems (e.g., asthma) which can be avoided by providing good ventilation.

In a future prototype, liquid metal may be incorporated into a touch-based display, allowing it to be touched with bare fingers using microchannels as in [48]; the electrolytic solution and conductive liquid metal would allow capacitive touch sensing. Alternatively, we might explore the potential for the technique in visual displays, for example by incorporating the liquid metal under a very thin flexible display (which will also enable unoccluded visualisation).

In terms of visual occlusion, Tangible Drops can be overlaid on digital content because the liquid (NaOH) is clear, and the drops could be moved to and from the reservoir on demand. Small drops will occlude the visible content minimally. Drops under the finger won't further occlude the display but will provide rich tactile feedback. In this work, we considered visual and tactile functionalities separately because the finger will already be occluding the visual content. In the future, we plan to develop applications by space- and time- multiplexing the visual and tactile features.

In Tangible Drops, the vibration frequency and amplitude depends on various operating parameters, including the drop size, electrode size and separation, and applied voltage. Future work in tactile perception and targeting on a tactile display will require careful evaluation and optimisation of the effect of these operating parameters.

## Use Cases

Considering applications of Tangible Drops, we note that they could be 1) directly controlled by a user's explicit interactions; 2) negotiated with the user; 3) indirectly controlled by the user's actions; and 4) fully controlled by the system [38]. They can be deployed for eyes-free or eyes-on use and create either visual, tactile or visio-tactile displays. Tactile information can be given by vibration, locomotion or a combination of both. Future work can explore this design space. For instance:

- To enable eyes-free prompting by the system to move the pointer under a user's finger to another part of the surface without the user having to look at the display: consider, then, a touch screen musical keyboard that provides tactile feedback to correct finger position.
- To allow eyes-free user control: e.g., for adjusting stage lighting via a mobile where Tangible Drops are used to create a feel-able slider (Fig. 1 (c)).
- To provide emphasis or attention-focusing properties to a digital visual display: consider, then, a map with the route being traced dynamically by the liquid metal (as in the animation presented in Fig. 1 (a)).

## CONCLUSION

We have presented Tangible Drops, which can produce visual animations on a flat surface using locomotion of liquid metal droplets. The enabling technology for the novel user experience that it provides is tactile feedback with 2D planar direction information using a liquid material. It demonstrates, for the first time, the locomotion of liquid metal drops from electrode to electrode on an open surface without constraining channels or cells. It also demonstrates for the first time a combination of locomotion and vibration of a material to provide tactile feedback. While this work is still in its prototype stage, we have shown it to be a viable new method of controlling liquid metal alloys for visio-tactile displays, and have therefore laid the foundations for what we hope to be a rich and full area of future work in the area.

## ACKNOWLEDGMENTS

This work was supported by EPSRC grants EP/N013948/1 & EP/M00421X/1.

## REFERENCES


1. Olivier Bau, Ivan Poupyrev, Ali Israr, and Chris Harrison. 2010. TeslaTouch: Electrovibration for Touch Surfaces. In *Proceedings of the 23Nd Annual ACM Symposium on User Interface Software and Technology (UIST '10)*. ACM, New York, NY, USA, 283–292. DOI: http://dx.doi.org/10.1145/1866029.1866074
2. G. Beni, S. Hackwood, and J. L. Jackel. 1982. Continuous electrowetting effect. *Applied Physics Letters* 40, 10 (1982), 912–914. DOI: http://dx.doi.org/10.1063/1.92952
3. Lynn Bickley and Peter G Szilagyi. 2012. *Bates' guide to physical examination and history-taking*. Lippincott Williams & Wilkins. pg. 632.
4. John William Boley, Edward L. White, and Rebecca K. Kramer. 2015. Mechanically Sintered GalliumâĂŞIndium Nanoparticles. *Advanced Materials* 27, 14 (2015), 2355–2360. DOI: http://dx.doi.org/10.1002/adma.201404790
5. Sung Kwon Cho, Hyejin Moon, and Chang-Jin Kim. 2003. Creating, transporting, cutting, and merging liquid droplets by electrowetting-based actuation for digital microfluidic circuits. *Journal of Microelectromechanical Systems* 12, 1 (Feb 2003), 70–80. DOI: http://dx.doi.org/10.1109/JMEMS.2002.807467
6. Kihwan Choi, Alphonsus H.C. Ng, Ryan Fobel, and Aaron R. Wheeler. 2012. Digital Microfluidics. *Annual Review of Analytical Chemistry* 5, 1 (2012), 413–440. DOI:http:

//dx.doi.org/10.1146/annurev-anchem-062011-143028 PMID: 22524226.

7. Marcelo Coelho, Hiroshi Ishii, and Pattie Maes. 2008. Surflex: A Programmable Surface for the Design of Tangible Interfaces. In *CHI '08 Extended Abstracts on Human Factors in Computing Systems (CHI EA '08)*. ACM, New York, NY, USA, 3429–3434. DOI: http://dx.doi.org/10.1145/1358628.1358869

8. Page M Crosby and A Lee Dellon. 1989. Comparison of two-point discrimination testing devices. *Microsurgery* 10, 2 (1989), 134–137.

9. Collin B. Eaker and Michael D. Dickey. 2016. Liquid metal actuation by electrical control of interfacial tension. *Applied Physics Reviews* 3, 3 (2016). DOI: http://dx.doi.org/10.1063/1.4959898

10. Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. inFORM: Dynamic Physical Affordances and Constraints Through Shape and Object Actuation. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology (UIST '13)*. ACM, New York, NY, USA, 417–426. DOI: http://dx.doi.org/10.1145/2501988.2502032

11. John Hardy, Christian Weichel, Faisal Taher, John Vidler, and Jason Alexander. 2015. ShapeClip: Towards Rapid Prototyping with Shape-Changing Displays for Designers. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 19–28. DOI: http://dx.doi.org/10.1145/2702123.2702599

12. Chris Harrison and Scott E. Hudson. 2009. Providing Dynamically Changeable Physical Buttons on a Visual Display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09)*. ACM, New York, NY, USA, 299–308. DOI: http://dx.doi.org/10.1145/1518701.1518749

13. David Holman and Roel Vertegaal. 2008. Organic user interfaces: designing computers in any way, shape, or form. *Commun. ACM* 51, 6 (2008), 48–55.

14. Liang Hu, Lei Wang, Yujie Ding, Shihui Zhan, and Jing Liu. 2016. Manipulation of Liquid Metals on a Graphite Surface. *Advanced Materials* 28, 41 (2016), 9210–9217. DOI:http://dx.doi.org/10.1002/adma.201601639

15. Sungjae Hwang, Kibeom Lee, and Woonseung Yeo. 2010. My Green Pet: A Current-based Interactive Plant for Children. In *Proceedings of the 9th International Conference on Interaction Design and Children (IDC '10)*. ACM, New York, NY, USA, 210–213. DOI: http://dx.doi.org/10.1145/1810543.1810573

16. Hiroshi Ishii, Dávid Lakatos, Leonardo Bonanni, and Jean-Baptiste Labrune. 2012. Radical Atoms: Beyond Tangible Bits, Toward Transformable Materials. *interactions* 19, 1 (Jan. 2012), 38–51. DOI: http://dx.doi.org/10.1145/2065327.2065337

17. Hiroo Iwata, Hiroaki Yano, Fumitaka Nakaizumi, and Ryo Kawamura. 2001. Project FEELEX: Adding Haptic Surface to Graphics. In *Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '01)*. ACM, New York, NY, USA, 469–476. DOI: http://dx.doi.org/10.1145/383259.383314

18. Sungjune Jang, Lawrence H. Kim, Kesler Tanner, Hiroshi Ishii, and Sean Follmer. 2016. Haptic Edge Display for Mobile Tactile Interaction. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 3706–3716. DOI: http://dx.doi.org/10.1145/2858036.2858264

19. Yvonne Jansen, Pierre Dragicevic, and Jean-Daniel Fekete. 2012. Tangible Remote Controllers for Wall-size Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. ACM, New York, NY, USA, 2865–2874. DOI: http://dx.doi.org/10.1145/2207676.2208691

20. Seung Hee Jeong, Anton Hagman, Klas Hjort, Magnus Jobs, Johan Sundqvist, and Zhigang Wu. 2012. Liquid alloy printing of microfluidic stretchable electronics. *Lab Chip* 12 (2012), 4657–4664. Issue 22. DOI: http://dx.doi.org/10.1039/C2LC40628D

21. Hiroyuki Kajimoto. 2012. Skeletouch: Transparent Electro-tactile Display for Mobile Surfaces. In *SIGGRAPH Asia 2012 Emerging Technologies (SA '12)*. ACM, New York, NY, USA, Article 21, 3 pages. DOI: http://dx.doi.org/10.1145/2407707.2407728

22. Tobias Kalisch, Jan-Christoph Kattenstroth, Rebecca Kowalewski, Martin Tegenthoff, and Hubert R. Dinse. 2012. Cognitive and Tactile Factors Affecting Human Haptic Performance in Later Life. *PLOS ONE* 7 (01 2012), 1–11. DOI: http://dx.doi.org/10.1371/journal.pone.0030420

23. Michael Stratan Karl Bridge, Alexander Koren. 2017. Guidelines for targeting. (8 February 2017). https://docs.microsoft.com/en-us/windows/uwp/input-and-devices/guidelines-for-targeting.

24. Mohammad Rashed Khan, Collin B Eaker, Edmond F Bowden, and Michael D Dickey. 2014. Giant and switchable surface activity of liquid metal via surface oxidation. *Proceedings of the National Academy of Sciences* 111, 39 (2014), 14047–14051. DOI: http://dx.doi.org/10.1073/pnas.1412227111

25. Khashayar Khoshmanesh, Shi-Yang Tang, Jiu Yang Zhu, Samira Schaefer, Arnan Mitchell, Kourosh Kalantar-zadeh, and Michael D. Dickey. 2017. Liquid metal enabled microfluidics. *Lab Chip* 17 (2017), 974–993. Issue 6. DOI: http://dx.doi.org/10.1039/C7LC00046D

26. Sugarragchaa Khurelbaatar, Yuriko Nakai, Ryuta Okazaki, Vibol Yem, and Hiroyuki Kajimoto. 2016. Tactile Presentation to the Back of a Smartphone with Simultaneous Screen Operation. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 3717–3721. DOI: http://dx.doi.org/10.1145/2858036.2858099

27. Hyunjung Kim and Woohun Lee. 2008. Shade Pixel. In *ACM SIGGRAPH 2008 Posters (SIGGRAPH '08)*. ACM, New York, NY, USA, Article 34, 1 pages. DOI: http://dx.doi.org/10.1145/1400885.1400922

28. Hyunjung Kim and Woohun Lee. 2011. Kinetic Tiles. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 1279–1282. DOI: http://dx.doi.org/10.1145/1978942.1979132

29. Collin Ladd, Ju-Hee So, John Muth, and Michael D. Dickey. 2013. 3D Printing of Free Standing Liquid Metal Microstructures. *Advanced Materials* 25, 36 (2013), 5081–5085. DOI: http://dx.doi.org/10.1002/adma.201301400

30. Daniel Leithinger, Sean Follmer, Alex Olwal, Samuel Luescher, Akimitsu Hogge, Jinha Lee, and Hiroshi Ishii. 2013. Sublimate: State-changing Virtual and Physical Rendering to Augment Interaction with Shape Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 1441–1450. DOI: http://dx.doi.org/10.1145/2470654.2466191

31. Daniel Leithinger and Hiroshi Ishii. 2010. Relief: A Scalable Actuated Shape Display. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '10)*. ACM, New York, NY, USA, 221–222. DOI: http://dx.doi.org/10.1145/1709886.1709928

32. Qiuyu Lu, Chengpeng Mao, Liyuan Wang, and Haipeng Mi. 2016. LIME: LIquid MEtal Interfaces for Non-Rigid Interaction. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA, 449–452. DOI: http://dx.doi.org/10.1145/2984511.2984562

33. Ken Nakagaki, Luke Vink, Jared Counts, Daniel Windham, Daniel Leithinger, Sean Follmer, and Hiroshi Ishii. 2016. Materiable: Rendering Dynamic Material Properties in Response to Direct Physical Touch with Shape Changing Interfaces. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 2764–2772. DOI: http://dx.doi.org/10.1145/2858036.2858104

34. Nam-Trung Nguyen, Majid Hejazian, Chin Hong Ooi, and Navid Kashaninejad. 2017. Recent Advances and Future Perspectives on Microfluidic Liquid Handling. *Micromachines* 8, 6 (2017), 186. DOI: http://dx.doi.org/10.3390/mi8060186

35. Ryuma Niiyama, Lining Yao, and Hiroshi Ishii. 2013. Weight and Volume Changing Device with Liquid Metal Transfer. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction (TEI '14)*. ACM, New York, NY, USA, 49–52. DOI:http://dx.doi.org/10.1145/2540930.2540953

36. Masa Ogata and Masaaki Fukumoto. 2015. FluxPaper: Reinventing Paper with Dynamic Actuation Powered by Magnetic Flux. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 29–38. DOI: http://dx.doi.org/10.1145/2702123.2702516

37. Pekka Parhi, Amy K. Karlson, and Benjamin B. Bederson. 2006. Target Size Study for One-handed Thumb Use on Small Touchscreen Devices. In *Proceedings of the 8th Conference on Human-computer Interaction with Mobile Devices and Services (MobileHCI '06)*. ACM, New York, NY, USA, 203–210. DOI:http://dx.doi.org/10.1145/1152215.1152260

38. Majken Kirkegård Rasmussen, Timothy Merritt, Miguel Bruns Alonso, and Marianne Graves Petersen. 2016. Balancing User and System Control in Shape-Changing Interfaces: A Designerly Exploration. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '16)*. ACM, New York, NY, USA, 202–210. DOI: http://dx.doi.org/10.1145/2839462.2839499

39. Simon Robinson, Céline Coutrix, Jennifer Pearson, Juan Rosso, Matheus Fernandes Torquato, Laurence Nigay, and Matt Jones. 2016. Emergeables: Deformable Displays for Continuous Eyes-Free Mobile Interaction. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 3793–3805. DOI: http://dx.doi.org/10.1145/2858036.2858097

40. A. Russomanno, Z. Xu, S. O'Modhrain, and B. Gillespie. 2017. A pneu shape display: Physical buttons with programmable touch response. In *2017 IEEE World Haptics Conference (WHC)*. IEEE, New York, NY, USA, 641–646. DOI: http://dx.doi.org/10.1109/WHC.2017.7989976

41. Satoshi Saga and Ramesh Raskar. 2012. Feel Through Window: Simultaneous Geometry and Texture Display Based on Lateral Force. In *SIGGRAPH Asia 2012 Emerging Technologies (SA '12)*. ACM, New York, NY, USA, Article 8, 3 pages. DOI: http://dx.doi.org/10.1145/2407707.2407715

42. Deepak Ranjan Sahoo, Kasper Hornbæk, and Sriram Subramanian. 2016. TableHop: An Actuated Fabric Display Using Transparent Electrodes. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 3767–3780. DOI: http://dx.doi.org/10.1145/2858036.2858544

43. Lei Sheng, Jie Zhang, and Jing Liu. 2014. Diverse Transformations of Liquid Metals Between Different Morphologies. *Advanced Materials* 26, 34 (2014), 6036–6042. DOI: http://dx.doi.org/10.1002/adma.201400843

44. Lisa Skedung, Martin Arvidsson, Jun Young Chung, Christopher M Stafford, Birgitta Berglund, and Mark W Rutland. 2013. Feeling small: exploring the tactile perception limits. *Scientific reports* 3 (2013), 2617.

45. Daniel Spelmezan, Deepak Ranjan Sahoo, and Sriram Subramanian. 2016. Sparkle: Towards Haptic Hover-Feedback with Electric Arcs. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16 Adjunct)*. ACM, New York, NY, USA, 55–57. DOI: http://dx.doi.org/10.1145/2984751.2985702

46. Cameron Steer, Simon Robinson, and Matt Jones. 2015. Growth, Change and Decay: Plants and Interaction Possibilities. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, 2037–2042.

47. Andrew Stevenson, Christopher Perez, and Roel Vertegaal. 2011. An Inflatable Hemispherical Multi-touch Display. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '11)*. ACM, New York, NY, USA, 289–292. DOI: http://dx.doi.org/10.1145/1935701.1935766

48. Tactus. 2012. Tactus: A New Dimension of Touch. (2012). Online White Paper : http://tactustechnology.com/wp-content/uploads/2014/08/White-Paper-New-Tagged-PDF.pdf - Accessed: 31//03/17.

49. Faisal Taher, John Hardy, Abhijit Karnik, Christian Weichel, Yvonne Jansen, Kasper Hornbæk, and Jason Alexander. 2015. Exploring Interactions with Physically Dynamic Bar Charts. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 3237–3246. DOI: http://dx.doi.org/10.1145/2702123.2702604

50. Shohei Takei, Makoto Iida, and Takeshi Naemura. 2011. KineReels: Extension Actuators for Dynamic 3D Shape. In *ACM SIGGRAPH 2011 Posters (SIGGRAPH '11)*. ACM, New York, NY, USA, Article 84, 1 pages. DOI: http://dx.doi.org/10.1145/2037715.2037810

51. Wouter M. Bergmann Tiest. 2015. Tactual perception of liquid material properties. *Vision Research* 109 (2015), 178 – 184. DOI: http://dx.doi.org/10.1016/j.visres.2014.08.002 Perception of Material Properties (Part I).

52. Yutaka Tokuda, Luis Jose Berna Moya, Gianluca Memoli, Timothy Neate, Deepak Ranjan Sahoo, Simon Robinson, Jennifer Pearson, Matt Jones, and Sriram Subramanian. 2017. Programmable Liquid Matter: 2D Shape Deformation of Highly Conductive Liquid Metals in a Dynamic Electric Field. In To appear in *the 12th ACM International Conference on Interactive Surfaces and Spaces (ISS '17)*. ACM, New York, NY, USA.

53. Philip Tuddenham, David Kirk, and Shahram Izadi. 2010. Graspables Revisited: Multi-touch vs. Tangible Input for Tabletop Displays in Acquisition and Manipulation Tasks. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. ACM, New York, NY, USA, 2223–2232. DOI: http://dx.doi.org/10.1145/1753326.1753662

54. Brett Victor. 2012. A Brief Rant on the Future of Interaction Design. (2012). Online Article: http://worrydream.com/ABriefRantOnTheFutureOfInteractionDesign/ - Accessed: 31//03/17.

55. Simon Voelker, Kjell Ivar Overgård, Chat Wacharamanotham, and Jan Borchers. 2015. Knobology Revisited: A Comparison of User Performance Between Tangible and Virtual Rotary Knobs. In *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces (ITS '15)*. ACM, New York, NY, USA, 35–38. DOI:http://dx.doi.org/10.1145/2817721.2817725

56. Akira Wakita and Akito Nakano. 2012. Blob Manipulation. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction (TEI '12)*. ACM, New York, NY, USA, 299–302. DOI: http://dx.doi.org/10.1145/2148131.2148193

57. Akira Wakita, Akito Nakano, and Nobuhiro Kobayashi. 2011. Programmable Blobs: A Rheologic Interface for Organic Shape Design. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '11)*. ACM, New York, NY, USA, 273–276. DOI: http://dx.doi.org/10.1145/1935701.1935760

58. M. F. Wang, M. J. Jin, X. J. Jin, and S. G. Zuo. 2017. Modeling of movement of liquid metal droplets driven by an electric field. *Phys. Chem. Chem. Phys.* 19 (2017), 18505–18513. Issue 28. DOI: http://dx.doi.org/10.1039/C7CP02798B

59. Xuelin Wang and Jing Liu. 2016. Recent Advancements in Liquid Metal Flexible Printed Electronics: Properties, Technologies, and Applications. *Micromachines* 7, 12 (2016). DOI:http://dx.doi.org/10.3390/mi7120206

60. T. White. 1998. *Introducing liquid haptics in high bandwidth human computer interfaces*. Master's thesis. MIT.

61. Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. 2013. PneUI: Pneumatically Actuated Soft Composite Materials for Shape Changing Interfaces. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology (UIST '13)*. ACM, New York, NY, USA, 13–22. DOI:http://dx.doi.org/10.1145/2501988.2502037

62. You-you Yao and Jing Liu. 2017. A polarized liquid metal worm squeezing across a localized irregular gap. *RSC Adv.* 7 (2017), 11049–11056. Issue 18. DOI: http://dx.doi.org/10.1039/C6RA28773E

63. J. Zhang, L. Sheng, and J. Liu. 2014. Synthetically chemical-electrical mechanism for controlling large scale reversible deformation of liquid metal objects. *Scientific Reports* 4, 7116 (2014). DOI: http://dx.doi.org/10.1038/srep07116