Droplet IO: Programmable Droplets for Human-Material Interaction

by

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Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning
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Abstract

In this thesis, I propose *aqueous droplets* as a form of *programmable material* that can *computationally transform* its physical properties. Liquid matter can undergo physical transformation through interfacial forces and surface tension. I introduce a system called DropletIO to regulate interfacial forces through a programmable electric field. The system can actuate and sense macro-scale (micro-liter to milli-liter) droplets on arbitrary planar and curved surfaces. The system can precisely move, merge, split, and change shape of droplets and thus enables a range of applications with human interactivity, information displays, parallelized programmable chemistry and dynamically tunable optics.

DropletIO system uses *electrowetting on dielectric (EWOD)* to manipulate droplets. EWOD is a physical phenomenon where a polar droplet on a dielectric surface is attracted to a charged electrode. I constructed EWOD arrays with integrated actuation and sensing on inexpensive printed circuit boards that can scale to arbitrarily large areas and different form factors. Additionally, in this thesis I discuss how semiconductor device scaling applies to electrowetting for smaller volume droplets and hence miniaturized *programmable lab-on-a-chip*.

Droplet based microfluidics is extensively used in biology and chemistry. In this thesis I describe two novel fluid manipulation mechanism for microfluidics. First, I show an approach for splitting aqueous droplets on an open digital microfluidic platform and thus a system capable of performing a complete set of microfluidic operations on an open surface. Second, I demonstrate how electrowetting platforms can handle large volume fluids, and hence enable a new direction in programmable fluid handling called *digital millifluidics*.

Thesis Supervisor: Hiroshi Ishii
Title: Jerome B. Wiesner Professor of Media Arts and Sciences

Acknowledgments

First and foremost, I would like to thank Hiroshi Ishii for building such an incredible lab, the Tangible Media Group, and bringing me into the group of creatives. I enjoyed the friction we have had over the two years. My time here gave me the freedom to envision crazy ideas and bring them to life. It is our shared dream to build computer interfaces with liquids and I believe this thesis is a good first step in this direction.

I thank Neil Gershenfeld for seeding the idea of manipulating droplets in the PIT class, which then became the foundation for my current work. I also thank Neil for putting together a lab with fabrication machines for manipulating materials at many scales. The first prototypes for DropletIO and this entire body of work would not be possible without the tools and extraordinary people in CBA.

I thank Skylar Tibbits for all the discussions and unique perspectives. Your inputs on how to drop conventional wisdom, identify interesting things within any body of work, and striking a balance between fiction and practicality will go a long way.

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The following people served as readers for this thesis:

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Contents

Chapter 1

Introduction

1.1 Programmable Materials to Programmable Droplets

Programmable Matter [82] proposes the concept of physical matter transforming from one object to another through dynamic shape change and material property transformation. This idea has inspired research in many fields including modular robotics [16], self-assembly [62, 76], origami folding [20, 30], and multi-functional materials [60] (Fig. 1-1). And in the field of human-computer interaction, Radical Atoms [25], Claytronics [17], and The Ultimate Display [66] propose general-purpose programmable materials that reconfigure their physical properties to form dynamic, malleable user interfaces. Driven by this vision, researchers have been creating materials and interfaces that change shape [14, 47, 59], texture [19, 78] and stiffness [13, 50].

DropletIO extends this approach by harnessing a natural material already present in our everyday environment: *aqueous droplets.* Water in the form of droplets is ubiquitous in nature and integral to our daily life. It has the ability to glide on a lotus leaf without wetting the surface, bundle hairy structures, carry chemical and biological materials, undergo phase-transition, entrap physical entities and bend light (Fig. 1-2). By treating water droplets as discrete, computationally controlled entities, DropletIO brings programmability to some of these properties. Such *programmable droplets* bring novel affordances to interacting with digital information.

A droplet, composed of polarizable liquid, changes its shape when a voltage is

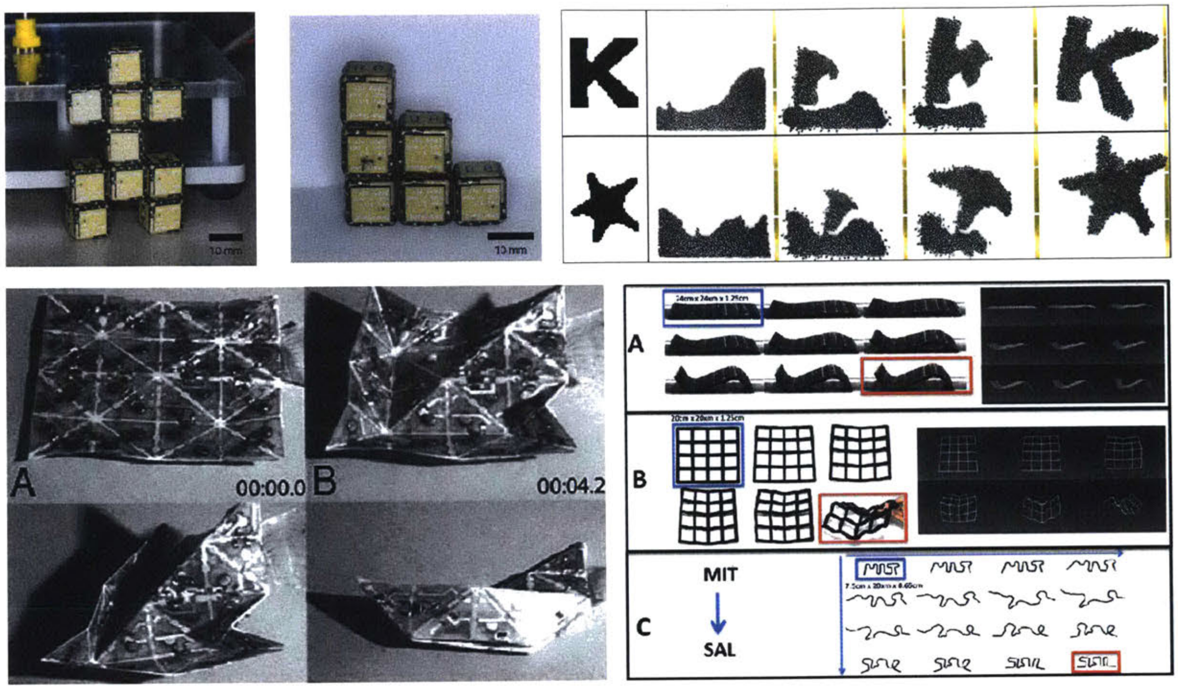

Figure 1-1: Programmable Matter Research. (a)Top Left: Modular Robots [16]. (b)Top Right: Self Reconfiguring Robots [62]. (c)Bottom Left: Programmable Matter by Folding [20]. (d)Bottom Right: Printed Materials for self-evolving deformations [60].

Figure 1-2: Natural phenomenon exhibited by droplets (left to right): bending of light rays, clumping of fibers, a droplet gliding on hydrophobic lotus leaf, ant trapped in a droplet.

applied across it. Through this phenomenon called *Electrowetting*, an aqueous droplet can be selectively pulled towards a positive electrode with increased wettability. By computationally controlling the electric field across an array of electrodes, a droplet can be repeatably moves across a surface. Based on this method, I develop a set of primitive operations, such as precisely translating, morphing, merging, and splitting multiple droplets.

To demonstrate how the DropletIO system can be integrated into everyday objects and spaces for a calm, ubiquitous display of information and interaction with computers [75], I fabricated electrodes on various rigid, flexible, transparent and opaque substrates. The backbone of DropletIO is a device made of an addressable array of electrodes, manufactured with standard PCB fabrication methods. I see DropletIO as a step towards the larger vision of pushing the paradigm of *computationally controlling physical materials* by introducing the idea of *programmable droplets* for human-material interaction.

1.2 Thesis Contribution

I summarize the thesis through the following contributions:

- The concept of droplets as versatile *programmable materials.*
- An electrowetting platform for high-speed actuation and sensing of macro-scale aqueous droplets that scales to arbitrarily sizes and form factors.
- An exploration of the design space in HCI and user interactions enabled by programmable droplets.
- A technical evaluation showing the challenges involved in up-scaling of electrowetting on Printed Circuit Boards.
- Two novel fluid manipulation mechanisms: splitting droplets on an open electrowetting platform and digital millifluidic droplet manipulation with electrowetting.

Chapter 2

Related Work

2.1 Programmable Force Fields

Programmable force fields for non-contact manipulation of physical objects has been somewhat explored in robotics and automation. Untethered micro-robots controlled with electric fields has been used as an approach for assembling micrometer scale objects [9, 10, 53]. SRI recently demonstrated tiny robots operated on circuit boards through magnetic fields [24] for automated assembly of millimeter objects. Since gravity dominates other forces at macro-scale, manipulation of physical material through force fields is not as straight forward. However, researchers have demonstrated use of holographic acoustic elements [42, 43] and arrays of air jets [5] for levitating lightweight objects such as tiny beads and sheets of paper. Other research groups have shown how acoustic fields can levitate and move macro-scale droplets in 3D space [1]. However, the nature of the acoustic field does not provide fine gran-

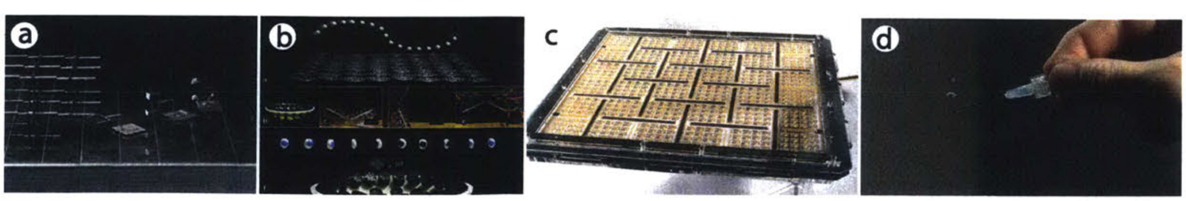

Figure 2-1: Programmable Force Fields.(a)Magnetically Levitated Microrobot [24]. (b)Holographic manipulation of particles [42]. (c)Planar manipulation of paper through airjet [5]. (d)Acoustic levitation of Macro-scale droplets [1].

ularity over precise control of droplets. *Electrowetting* is an established technique which provides fine control over manipulating droplets and provides versatile droplet operations. This is the method of choice for manipulating droplets per the goals set in this thesis.

2.2 Electrowetting

The process of electrically moving liquid has existed since 1875 – when Gabriel Lippman experimentally showed a change in mercury level in an electrolyte solution under an applied voltage (i.e. *electro-capillarity* [37]). The next major work using this principle occurred almost a century later: researchers actuated a droplet on an electrode for use in an information display [4]. This actuation came to be known as *electrowetting.* This first iteration was limited by the direct contact between the droplet and electrodes. Even at low voltages, water undergoes electrolysis and become gaseous. This problem was later solved by Berge when he added a thin dielectric film between the droplet and the metal electrodes [70]. The phenomenon called *electrowetting on dielectric (EWOD)* propelled a whole field of research with first applications in variable focus liquid-lenses [34, 71]. Additionally, significant work has been done on using liquid in liquid electrowetting for paper like displays [4, 38]. However, a larger interest in the technique came after pioneering work by Pollack and Fair at Duke University [55]. They showed the applicability of EWOD for droplet microfluidics and popularized the term *digital microfluidics* [12]. The DropletIO platform is built on the same principles of *Electrowetting on Dielectric (EWOD)*, where the wettability of any aqueous liquid can be modulated through an electric field across a dielectric film between the droplet and conducting electrode. This makes it possible for DropletIO to manipulate virtually any aqueous liquid.

2.3 Microfluidics and Programmable Chemistry

Using electrokinetic forces to handle small volume fluids is a very well studied subject matter in microfluidics, specifically for biochemical applications. Handling fluids in the form of discrete droplets through an external field is termed as *digital microfluidics.* Basic droplet operations such as dispensing, transport, and merging have been demonstrated through techniques such as surface acoustic waves (SAW), thermocapillarity and dielectrophoresis. Although, dielectrophoresis a technique which uses a spatially non-uniform electric field to manipulate polarizable materials is commonly used in cell separation [23] its suitability for digital microfluidics has been extensively studied [2]. A closely related phenomenon, electrowetting is more common in droplet microfluidics due to versatile droplet operations it offers and its suitability with many fluids.

The programmable nature of electrowetting makes it very attractive as a platform for many applications in chemistry and biology. Early work on electrowetting showed the promise of being the platform for a true lab-on-chip [65]. Since then, digital microfluidic devices have been shown to have wide variety of applications including automated assays [65], point of care diagnostics [65], library preparation for next gen sequencing [29], and more recently synthesis and cloning of cell-free DNA [81].

2.4 Computing with fluids

Analog fluidic devices and digital fluidic logic is an alternate approach to computationally manipulate fluids. Use of fluidics for computing has existed for several decades. The MONIAC is an early analogue computer built on fluidic logic to model problems in economics [6]. Preliminary work on building fluidic circuits [3], logic gates and computers [8] with inertial interactions was done in the 1960s. Cheow et al. [7] and Prakash et al. [58] demonstrated how universal logic can be performed with droplets in microfluidic chambers and bubbles in microfluidics, respectively. Furthermore, Mertaniemi et al. [44] showed how colliding droplets on a super hydrophobic surface (liquid-air interface) can be used for constructing logic gates and programmable chemistry.

2.5 Solid/Fluid Manipulation for Interaction Design

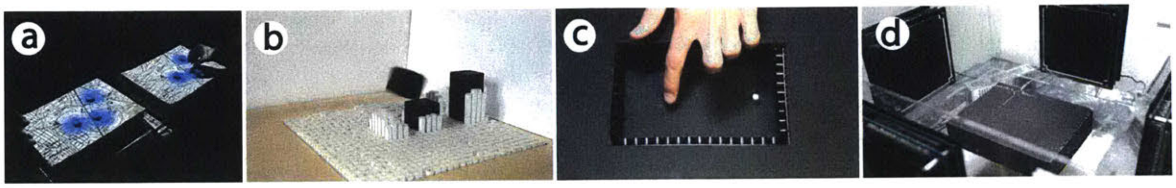

Figure 2-2: Solid Manipulation in HCI.(a)Actuated workbench with Electromagnets. (b)Manipulating physical blocks on a Shape display. (c)Acoustic Haptics. (d)Acoustic mid-air 3D display.

In the field of HCI, various research groups have explored ways to manipulate physical objects for kinetic displays and tangible interactions. For example, researchers have been moving solid objects using electromagnets [51], pin-based shape displays [63], and ultrasonic acoustic manipulation [41, 48].

Manipulating fluid materials has been explored for enabling non-rigid interactions. For instance, HydroMorph presented a system for manipulating shapes of water membrane created under a stream of water as kinetic interactive display [46]. Ferrofluid has been often used for texture-changing organic surfaces or interactive kinetic sculptures [31, 32]. Heiner et al. presented an ambient display composed of air bubbles rising up tubes of water [22].

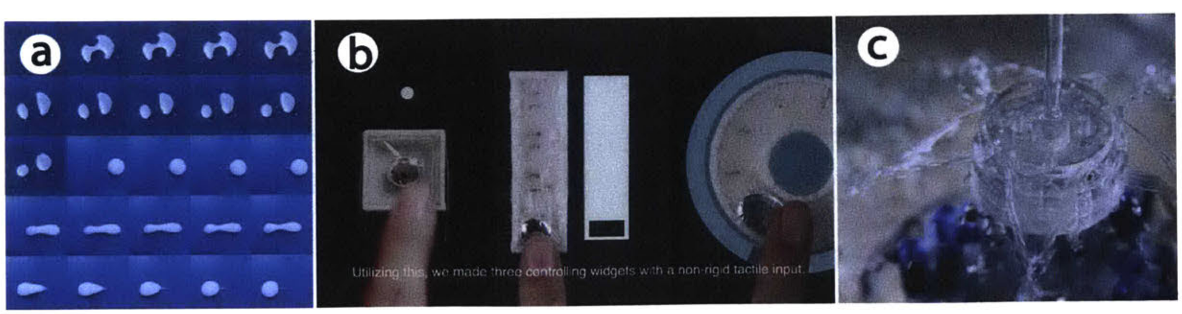

Figure 2-3: Fluid Manipulation in HCI. (a)Shape-changing Ferrofluid blob [72]. (b)Liquid Metal Interface [40]. (c)Kinetic Interactive Display [46].

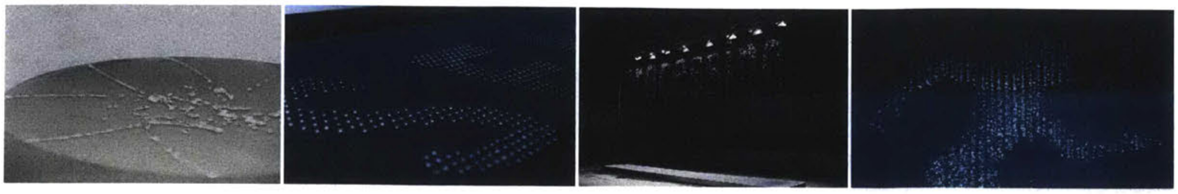

Figure 2-4: Droplets as display.

Fluids in the form of droplets and blobs have been explored in HCI as a medium for interaction 2-4. Polka Dot utilized a hydrophobic fabric on top of a shape display for controlling the motion of droplets as a tangible interface [33]. Wakita et al. presented a series of interactive interfaces based on shape changing blobs of ferrofluid, actuated by an array of electro-magnets [72, 73]. LIME used liquid metal with an external electric field stimulus for visual and tangible interaction [40]. A number of artworks make use of the aesthetic and expressiveness of falling droplets as a display [28, 49, 57].

DropletIO, using the principle of electrowetting, focuses on the precise droplet manipulations on a planar surface, rather than relying on gravity. As the system works with water, the droplets are safe for users to have direct touch interactions.

Chapter 3

Electrowetting on Dielectric: Operation principle

Wettability of a liquid refers to how a liquid deposited on a solid surface spreads. The wettability of a droplet on a solid surface surrounded by air is governed by interfacial tension between the solid, liquid and gas medium. For an immobile droplet, the wettability is measured in terms of the contact angle with the solid surface, which is governed by Young's equation (Eq. (3.1)),

$$\gamma_{SL} = \gamma_{SG} + \gamma_{LG} \cos \theta_e \tag{3.1}$$

where γ_{SL} is the solid-liquid surface tension, γ_{LG} is the liquid-air surface tension, γ_{SG} the solid-gas surface tension θ_e is the contact angle under equilibrium.

Gabriel Lippman, in 1875, noticed electrocapillarity, where the capillary level of mercury in an electrolyte would change when a voltage is applied. This phenomenon is then described through Lippmann-Young's equation (Eq. (3.2)),

$$\cos \theta_v = \cos \theta_0 + \frac{1}{\gamma_{LG}} \frac{1}{2} c V^2 \tag{3.2}$$

θ_0 is the contact angle when the electric field is zero (i.e. no voltage applied) and θ_v is the contact angle when a voltage V is applied, and c is the capacitance per unit area between the electrode and the droplet. As represented by Equation 3.2, the

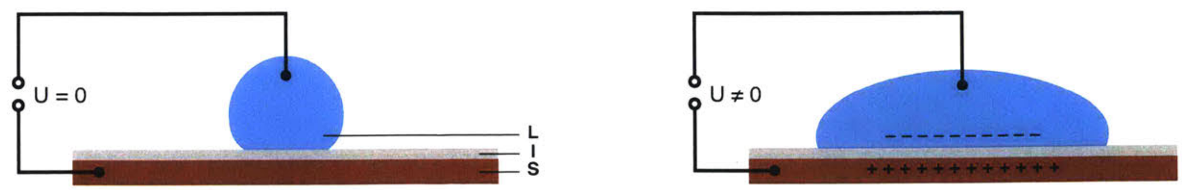

Figure 3-1: (a) Electrowetting operating principle. (b) Droplet wetting when a voltage is applied (actual image will be placed later)

contact angle is a function of the applied voltage as is illustrated in Fig. 3-1

3.1 Moving Droplets

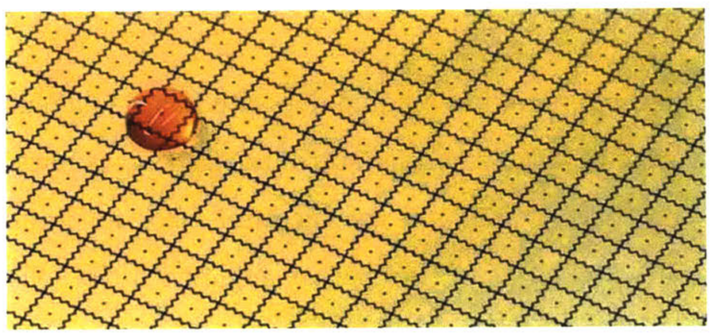

Figure 3-2: Droplet on an electrode array

Consider a droplet on an array of electrode as in Fig. 3-2. Applying a voltage to an electrode makes the surface hydrophilic and a droplet can then wet in. When no voltage is applied to the electrode, the surface returns to original hydrophobic state and the droplet is naturally repelled, as shown in Fig. 3-3. By sequentially controlling the voltage applied to an electrode grid (visualized in Fig. 3-2), a droplet's position on a surface can be precisely controlled.

3.2 Merging Droplets

Merging two droplets is an extended version of droplet motion. When two droplets are pulled towards the same electrode, they naturally coalesce due to surface tension

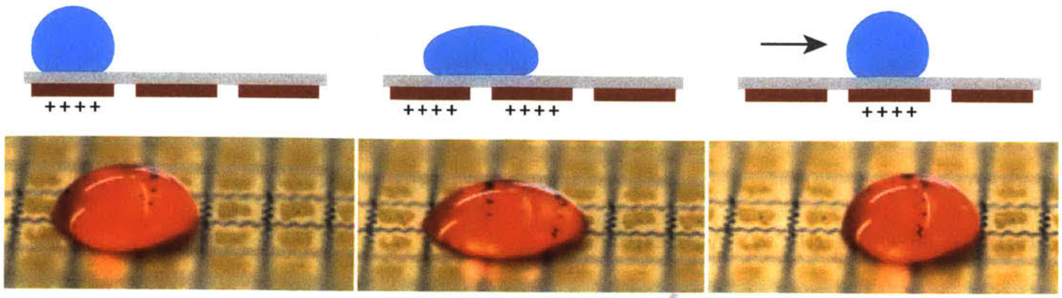

Figure 3-3: Droplet moving across two electrodes

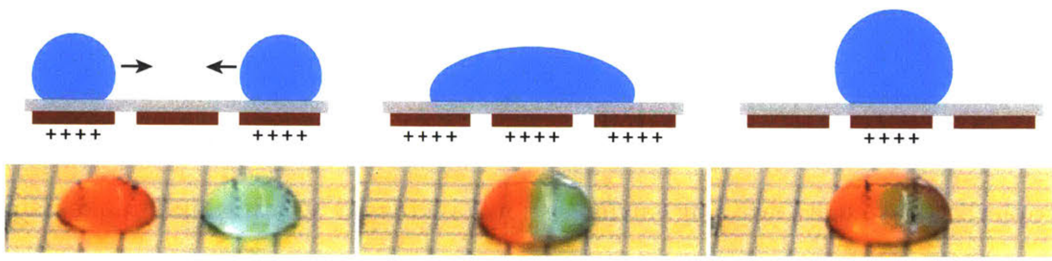

Figure 3-4: Droplet Merging

(2Fig. 3-4). This principle can be applied to merge a number of droplets to create a larger volume droplet spreading across multiple electrodes.

3.3 Splitting Droplets

A droplet can be split into two smaller ones through a sequence of voltages, applied across multiple electrodes (at least three) as in Fig. 3-5. First, a single droplet is spread across three adjacent electrodes by applying equal voltage to all of them

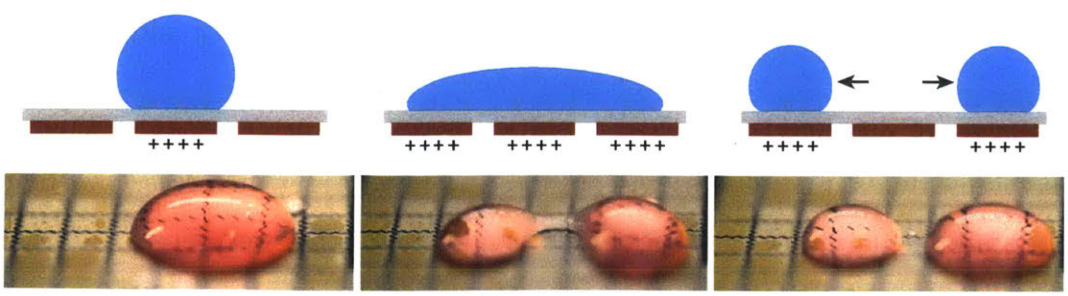

Figure 3-5: Splitting Droplets

simultaneously. Turning off the center electrode forces the droplet to move in either direction, due to neighboring active electrodes. The droplet then splits into two smaller ones. Splitting a droplet in to two smaller ones requires significantly larger force than what is required to move or merge, hence the voltages used to split the droplets are also significantly higher.

Dispensing fluids as droplets from a reservoir is another operation that is frequently useful in droplet based microfluidics. This is achieved by asymmetrically cleaving a droplet through the split operation.

3.4 Spreading Droplets

A droplet on an electrowetting surface shows increased wetting and makes smaller contact angle when a voltage is applied. Amongst many parameters, the applied voltage regulates the extent of wetting. This spreading behavior can be used in applications such as liquid lenses with variable focal length and information displays. The droplet can be spread and unspread at very high switching frequencies and thus suitable for rapid focal changes and video-speed displays.

3.5 Mixing Operation

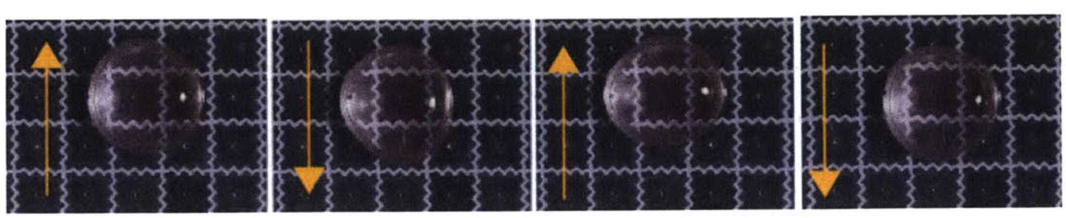

Figure 3-6: Homogeneous mixing by moving a droplet back and forth.

Mixing two droplets is a typical operation performed in digital microfluidics. In small volume fluids (microliters), viscous forces dominate inertial forces (low Reynolds number fluids) and at low velocities fluids usually do not mix well. Since diffusion due to thermal motion is also slow, mixing is typically achieved by introducing turbulence in the flow by increasing velocity.

With the large droplets (tens of microliters) in an unconstrained space as in DropletIO, mixing is rapid due to the surface waves introduced by collision of two droplets. Additionally, to ensure homogeneous mixing simple measures have to be taken such as moving the merged droplets back and forth across multiple electrodes as shwon in Fig. 3-6.

Chapter 4

Hardware Design and Construction

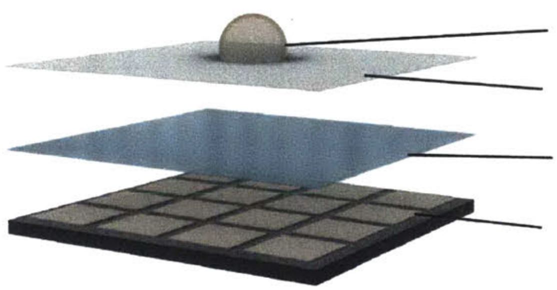

Figure 4-1: Droplet on an open single plate.

A typical DropletIO hardware consists of electrode array, a layer of dielectric, hydrophobic coating and electronics for actuation and sensing; see Fig. 4-1. In this chapter I will go in to the details of design choices for each element.

For electrowetting droplet manipulation, a droplet can either be placed on an open surface (single plate) or sandwiched between two plates (double plate); see Fig. 4-2. In DropletIO, I chose to work with single plate, since the open nature of the device enables touch interaction, and easy addition/removal of large volume fluids. Additionally, in this configuration, the droplet has a convex meniscus and thus can handle large volume droplets.

In the double plate configuration (Fig. 4-2), a droplet is sandwiched between two plates, typically separated by 100 μm – 300 μm. The double plate configuration has

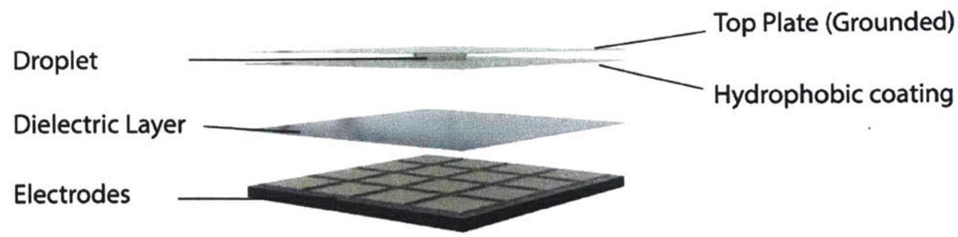

Figure 4-2: Droplet sandwiched between two plates.

electrodes on one side while the other acts as a ground plane. In contrast to single plate configuration, this configuration provides stronger force penetrating the droplet and hence robust control over droplets and the ability to split droplets at a lower actuation voltage.

4.1 Substrate Property

Substrate	Rigidity	Opacity	Temperature Stability (°C)
Glass	Rigid	Transparent	550
PET	Flexible	Transparent	250
Kapton	Flexible	Opaque	400
FR4	Rigid	Opaque	185

Table 4.1: Rigidity and Opacity of substrates

The substrate for constructing electrowetting arrays can have different mechanical and optical properties; it is selected based on the application needs. Table 4.1 compares typical substrates used for fabricating DropletIO devices. A transparent substrate is suitable for electrowetting based displays, programmable lenses and to perform insitu optical measurement in analytical chemical applications. A rigid substrate provides a solid and planar interaction surface for human interaction and for robotic fluid handling systems that interface with electrowetting digital microfluidic devices. A flexible substrate such as PET (Polyethylene terephthalate) or Kapton (polyimide film developed by DuPont) is suitable for fabricating flexible displays and programmable optics.

Dielectric	Thickness (μm)	Dielectric Strength	Surface Energy (mN/m)
Saran Wrap (PVDC)	10	160 - 280 kV/mm	45
Parafilm	12	10 kV/mm	65
PDMS	5	500 V/μm	19.3
Teflon (PTFE)	5	260 kV/mm	20

Table 4.2: Dielectric film and their properties

4.2 Dielectric Film

A droplet in direct contact with a positive electrode undergoes electrolysis, at relatively low voltages. However, a water droplet isolated from an electrode by a thin dielectric membrane is still under the influence of the electric field and undergoes polarization. The electric field intensity is a function of the distance from the charge and the it decays very rapidly ($E = k * Q/d^2$, E is field intensity, d is the distance). Hence the dielectric film separating the droplet from the electrode can not exceed a few micrometers. And at these thicknesses, the material should have sufficiently large dielectric constant to not breakdown under high voltages.

Typically dielectric materials tend to exhibit hysteresis in polarization and sometimes the polarization can be irreversible. A local irreversible polarization of the dielectric film can keep a droplet permanently trapped at a location. Successful movement of a droplet from one electrode to another is dependent on the reversible polarization of the dielectric film. Typically for a dielectric reversible polarization is characterized by the parameter dielectric relaxation. Electrowetting literature review shows experimental results on reversibility of various dielectric materials. The most common used dielectric with reasonable reversibility include Teflon films, Silicon Dioxide and Parylene. However, these materials were either expensive, difficult to procure, or would require specialized processes to apply on to PCB electrodes. Hence, I chose to work with readily available materials which provide acceptable results for a prototype. Table 4.2 lists all the material that I experimented with and for most application demonstrated in DropletIO, stretched Parafilm and tensioned PTFE worked best.

4.3 Hydrophobic Coating

Figure 4-3: Droplet on (a) raw PTFE film and (b) Silicone Oil coated PTFE film. Droplet exhibits slightly increased contact angle. Although the contact angle change is small, Silicone Oil makes the PTFE film surface slippery.

The contact angle of a immobile droplet on a solid surface arises from the surface tension between the droplet and the solid surface. This tension is between surface forces in the droplet and the solid. As seen in Table 4.2, Teflon and PDMS have the least surface energy with resulting contact angles of 107° and 112° respectively for a water droplet; see Fig. 4-3. While previous research shows many different approaches to achieve hydrophobicity by modifying surface properties, within the timeframe of the thesis, I chose to use the simple method of applying Silicone Oil on the Teflon and the PDMS surfaces. Both approaches seem to provide reasonably good results for droplet manipulation. Further details on coating is discussed later in construction and evaluation section.

However, a robust hydrophobic coating for extended periods of use still remains a challenge. Considerations for engineering the bulk and surface properties of the dielectric material, and an approach to accomplish a robust coating will be discusses in the performance evaluation section.

4.4 Fabrication Method

The smallest droplet size that can be manipulated is a function of the size of the electrode and the spacing between electrodes. This is essentially governed by the feature size of the fabrication process. The feature size becomes crucial in the process of scaling electrowetting arrays for manipulating nanoliter and picoliter droplets. Within the scope of the thesis, I narrowed down the investigation to two PCB manufacturing processes – dry laser etching and photolithography with wet etching.

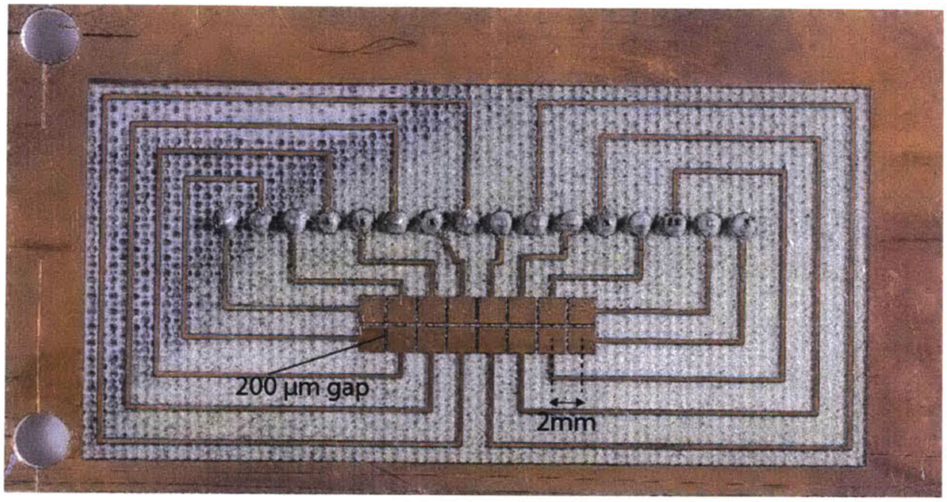

Figure 4-4: Fiber Laser etched Electrode Grid.

The first prototypes with 40 μm feature size were made on the Fiber Laser machine (Trotec Speedy 100 Flexx). The process involves etching away copper on a regular Copper Clad board. Although this is a quick and easy way to make electrodes (PCBs in general), the process is restricted to single sided boards. This limits the complexity of routing and hence the electrode geometry is limited to linear arrays 4-4.

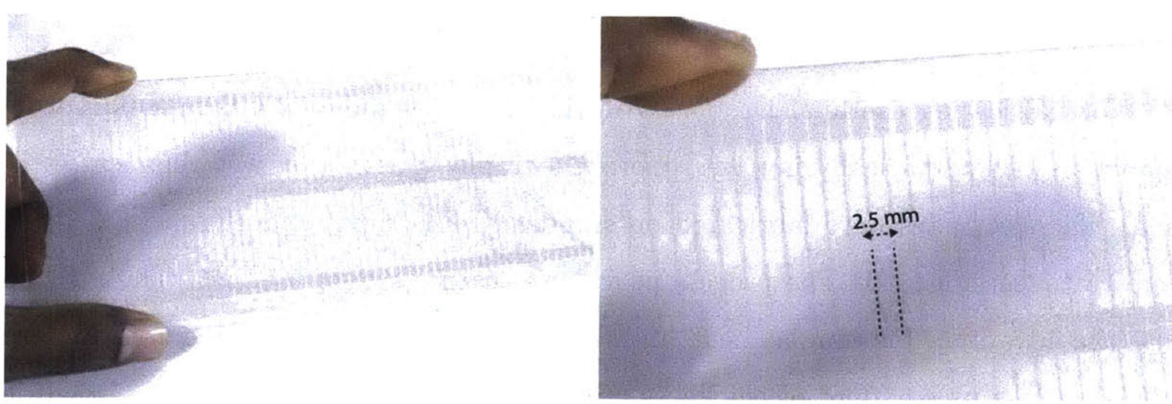

Figure 4-5: Laser etched transparent electrode on ITO-Glass substrate.

Fully transparent electrodes were made on ITO coated glass (rigid) and ITO

Process	Feature size	Electrode Geometry
Fiber Laser etching	40 μm	Linear Array
Dry Laser Lithography	5 μm	Linear Array
Commercial PCB	100 μm	2D Grid

Table 4.3: PCB processes and capabilities.

coated PET (flexible) as the substrate; see Fig.4-5. Dry Laser etching with ablation gives a feature size of 5 μm. The process suffers from the same limitation as the fiber laser process with copper; only linear arrays are possible.

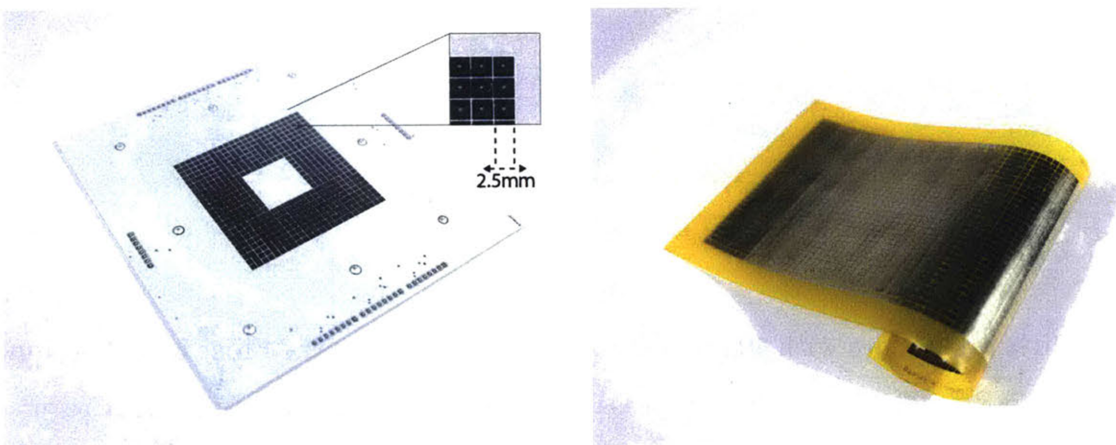

Figure 4-6: Rigid (Left) and Flexible (Right) Electrodes fabricated with standard PCB manufacturing processes.

For fabricating the final DropletIO device, I used standard PCB manufacturing processes, which typically involves photolithography followed by wet chemical etching. The electrodes were fabricated on standard FR4 (rigid) and Pyralux (flexible) substrate; see Fig. 4-6. The process provides a feature size of 100 μm. The method has the advantage of being a cheap and fast way to scale electrowetting. A standard PCB process uses copper of thickness at least 35 μm (1oz per foot). The isolation between two electrodes which is now 35 μm deep, introduces sufficiently large roughness to inhibit droplet motion. I solve this by modifying the surface with a dielectric film and hydrophobic coating.

4.5 Construction

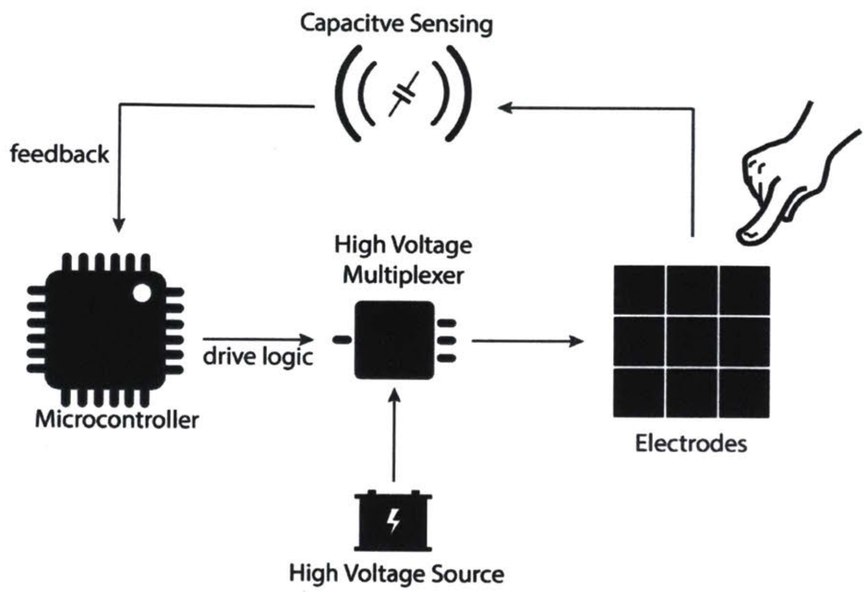

Figure 4-7: System overview.

Fig. 4-7 shows the main components of the DropletIO hardware: Electrodes, a high voltage drive circuit, a capacitive sensing unit, and a microcontroller.

4.5.1 Electrodes

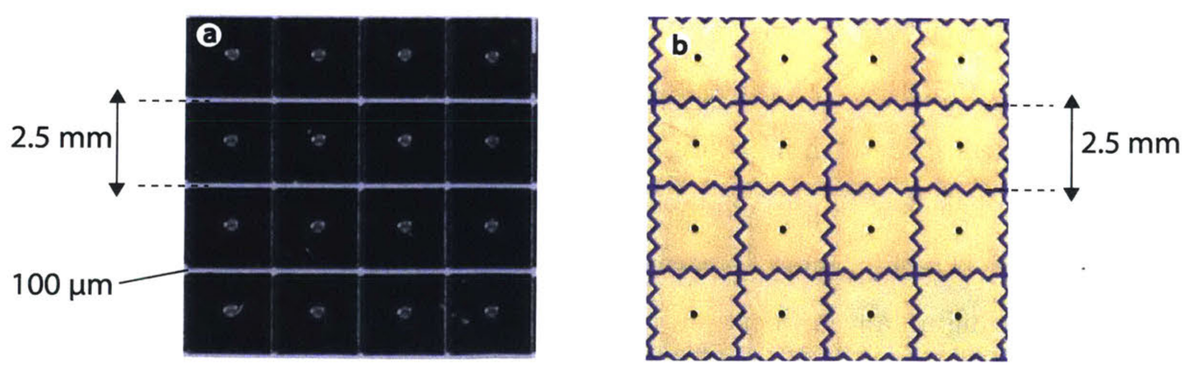

Figure 4-8: Left: Square electrode geometry. Right: Serrated electrode geometry.

DropletIO uses an electric force field generated on an electrode grid to regulate the wettability of droplets on a solid surface. The electrodes can be arranged in different shapes and layouts; for example linear arrays (Fig. 4-4, 4-5) and grids (Fig. 4-6). The geometry of the electrodes influence the electric field pattern and hence the manipulability of droplets. A thorough analysis of dynamics between the electric field and droplet arising from different geometry was studied in detail by Lienemann et al[36]. Based on their investigation, for this thesis I chose electrodes with simple square geometry (Fig. 4-8 (a)) and serrated square geometry (Fig. 4-8 (b)). Introducing small serrations at the edges introduces overlapping fields and a gradient in electric field that generates a force that propels the droplet when electrodes are switched.

The dimensions of the electrode has a direct effect on smallest manipulable droplet size and the extent of control. A finer granularity of electrodes provide a higher resolution for the electric field and make a seamless transition of droplets possible, but also results in more complex PCBs and driving circuits. While it is possible to make electrowetting arrays with micron resolution electrodes and gaps, DropletIO uses millimeter-scale electrodes with a size of 2.5 mm x 2.5 mm each, and a 100 μm gap between each electrode; see Fig. 4-8. This size is straightforward to produce with standard PCB manufacturing methods, and the droplet size is well suited microliter droplet manipulation in digital microfluidics and for human interaction.

4.5.2 Preparing PCB Electrode Surface for Droplet Motion

Electrodes on a PCB from a typical fabrication facility are not fully ready for manipulating droplets. The etching process introduces valleys that are at least 35 μm. I apply a thin dielectric film to eliminate these valleys to smooth the droplet manipulation surface. The film must be carefully applied to achieve a uniformly flat surface without creating an air gap between the electrodes and the film.

Fig. 4-9 a shows the different layers that makes up the finished electrode for droplet manipulation. The electrodes are first covered with a thin film of dielectric and then coated with hydrophobic material. Research literature shows a wide variety of dielectric and hydrophobic coating suitable for electrowetting. In DropletIO, I

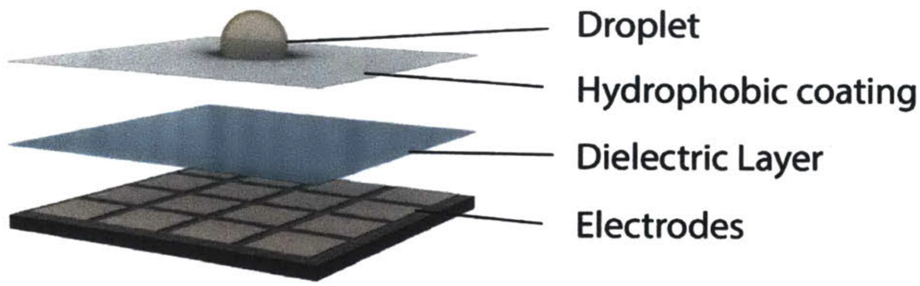

Figure 4-9: Droplet on an open single plate.

started with a combination of Saran wrap [57] and Peanut oil as the dielectric and hydrophobic coating [30] respectively. Of the materials I tested, a combination of Parafilm and Silicone oil provided the most robust surface and smoothest droplet motion. I developed a specialized process for stretching and applying the Parafilm on to the PCB surface. Parafilm being a compliant material, it can mask the surface roughness of the electrodes and the gaps between them. The Parafilm with Silicone oil functions as a liquid-infused film providing a liquid-liquid interface for the droplet to glide gently.

4.5.3 Hardware: Actuation and Sensing

An AVR microcontroller performs all the logic to generate drive signals for the electrodes and to process feedback obtained from the capacitive sensing unit (Fig. 4-10).

High Voltage Drive

The required actuation voltage for droplet motion is a function of the thickness of the dielectric. For a dielectric film of 12 μm thickness, the minimum actuation voltage is a 275 V DC, while it is 65 V for a 5 μm film. While stronger forces can be derived from AC signals on the electrode, to reduce complexity of drive circuitry I chose to use a simple DC drive. I re-purposed a Nixie Power Supply [11] as a high-voltage source. For driving the electrodes, I used a 64 bit Serial to Parallel Shift register HV507 and a 8 bit Serial to Parallel Shift register HV513, both from Microchip Technology

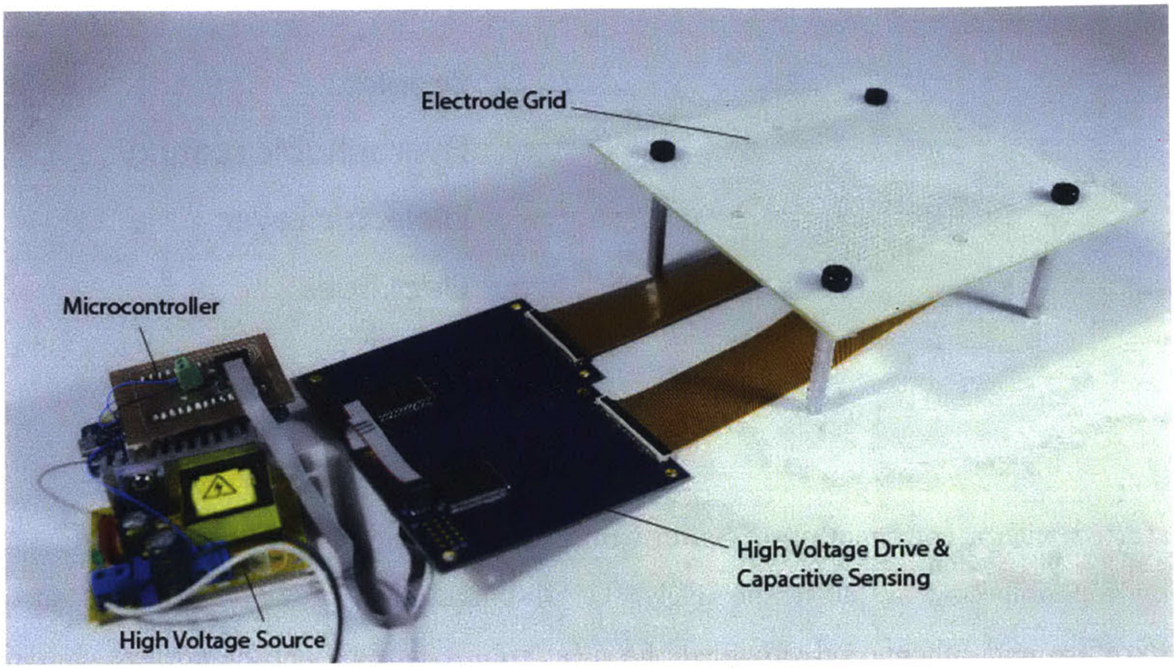

Figure 4-10: DropletIO setup.

(Chandler, AZ, USA). Each electrode on the grid is driven individually by a high voltage pin on a Shift registers. Thus each electrode is uniquely addressable.

Droplet Sensing

A capacitive sensing unit was implemented on a Cypress PSoC4 device (Cypress Semiconductor Corp., San Jose, CA, USA) to probe every electrode individually. The implementation can sense partial and complete presence of a droplet on an electrode and allows for feedback and error correction in droplet motion. In addition, the capacitive sensing also enables to determine the size and contents of a droplets, as well as touching a droplet by a hand.

The sensors scan each electrode at 3kHz. With a 16 bit resolution on the signal, droplets differing in diameter by 0.5mm can be accurately distinguished. The sensing signal had sufficient range to detect a human hand approaching a droplet. When an electrode is scanned for capacitance, adjacent electrodes were grounded to prevent coupling between electrodes. Partial presence of a droplet on multiple pads is detected through individual signal levels.

Chapter 5

Scaling Electrowetting and Digital Millifluidics

Microfluidics is beginning to see its use as a production tool in pharmaceuticals and synthetic biology. Many of these applications demand integration of multiple functionalities in to a single device. Programmable electrowetting arrays have the potential for achieving this kind of integration at large scale for versatile operations, parallelization, and miniaturization.

In this chapter, first, I describe how microfluidic systems suffer from *tyranny of numbers*. Second, I discuss problems with scaling electrowetting arrays to denser and larger arrays with DropletIO and their corresponding solutions. Finally I propose a framework for multi-scale fluid handling in a single system.

5.1 Tyranny of Numbers

In the early part of the 20th century, the electronics industry faced a problem which is referred to as the "tyranny of numbers": there is a practical limit to how complex a circuit can be with discretely assembled macroscopic components [61]. For example, the early computers such as ENIAC consisted of 17500 vacuum tubes, $5,000,000$ hand-soldered joints, weighed about 30 tons, was roughly $2.4m \times 0.9m \times 30m$ in size, occupied $167m^2$ and consumed 150 kW of electricity. Even when large vacuum

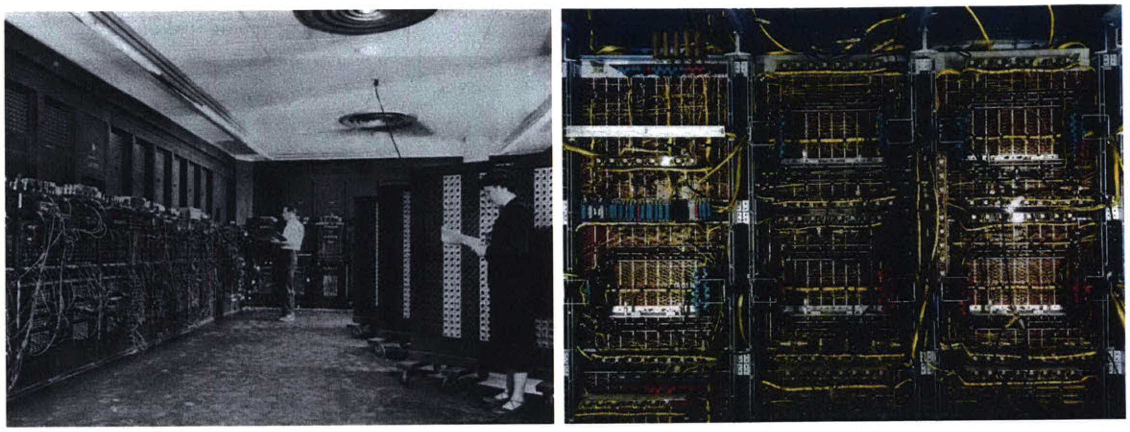

Figure 5-1: Left: ENIAC computer with 17500 vacuum tubes and 5,000,000 hand soldered joints. Right: UNIVAC computer with 5000 vacuum tubes.

tubes were replaced with smaller transistors, manual soldering of individual external component was cumbersome and prone to errors.

Current microfluidic technologies require the integration of many complex functions in to a single device. This involves fabrication of the microfluidic chip for logic and control of fluids, their interfacing with external pressure source, storage elements, valves and tubes. Today, the most advanced systems in the industry and research labs integrate such systems manually. There is no scalable process for integrated assembly of such systems. This lack of scalability in microfluidics is analogous to the large scale integration of electronics – both suffer from the *tyranny of numbers.*

5.2 Solution to Tyranny of Numbers

Complex circuits with millions of transistors and interconnects was possible with the invention of Integrated Circuits by Kilby and Noyce. The *tyranny of numbers* problem for electronics was solved with this single integrated process for fabricating resistors, capacitors, transistors and interconnects in one package.

Thorsen et al. [67] attempted to create methods for Microfluidic Large Scale Integration. They fabricated a microfluidic device with 2056 microvalves and 256 storage chamber in a single soft lithography process; see Fig. 5-2. Their architecture can run up to 256 distinct reactions in the chambers; this device was specifically targeted

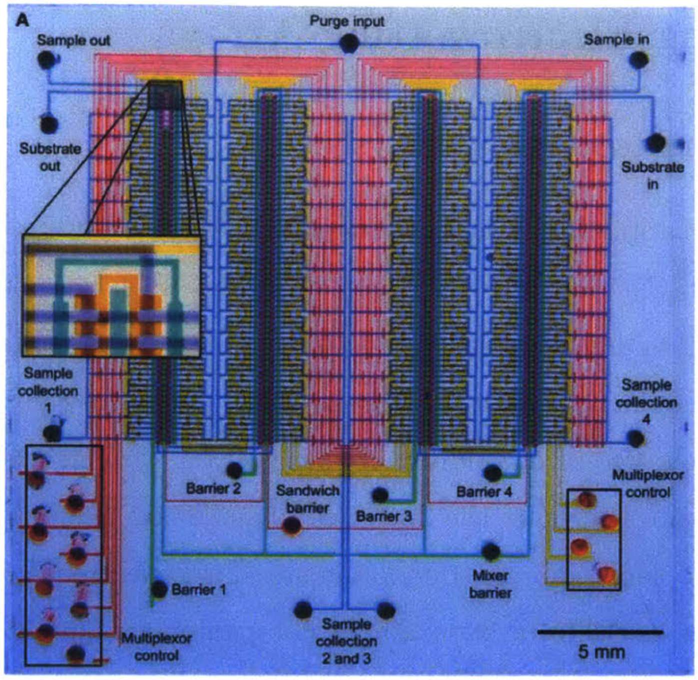

Figure 5-2: Microfluidic Large Scale Integration by Thorsen et al. [67].

for applications such as automated chemical assays. Although this is a promising direction, their approach still relies on external pressures sources, tubes and valves. The manual assembly of the external components introduces complexity in very large scale integration. And most importantly, their approach does not show a path to achieve complete programmability.

Digital Microfluidics on electrowetting arrays eliminates the need for pressure sources, tubes and valves entirely, and, provides programmable control over droplet paths. The same programmable surface can be reconfigured for many different applications. Since the device is entirely electronic it has the potential to scale to Very Large Scale Integration. In DropletIO, a programmable 2D grid provides a reconfigurable routing for various experiments and direct addressing allows for parallel manipulation of large number of droplets. I chose to use standard PCB fabrication since it scales to large areas inexpensively. In the next section, I will discuss the scalability of this approach to larger and denser arrays.

5.3 Scaling Electrowetting Arrays

5.3.1 Scaling to Large Arrays

The most recent DropletIO device consists of 2048 electrodes (32×64 grid) driven by 32 discrete driver ICs, and measures $85mm \times 170mm$. With each electrode measuring $2.5mm \times 2.5mm$, the area occupied by electrodes collectively, is the same as that of all the electronic components. With this 1:1 size ratio, the device can scale to arbitrarily large areas without requiring additional space for the driving electronics. At this size ratio, the smallest droplet the device can handle is 2 microliters. Manipulating sub-microliter droplets requires reduction in size of the electrodes. A 100μm (feature size of PCB process) electrode for example can manipulate nanoliter droplets.

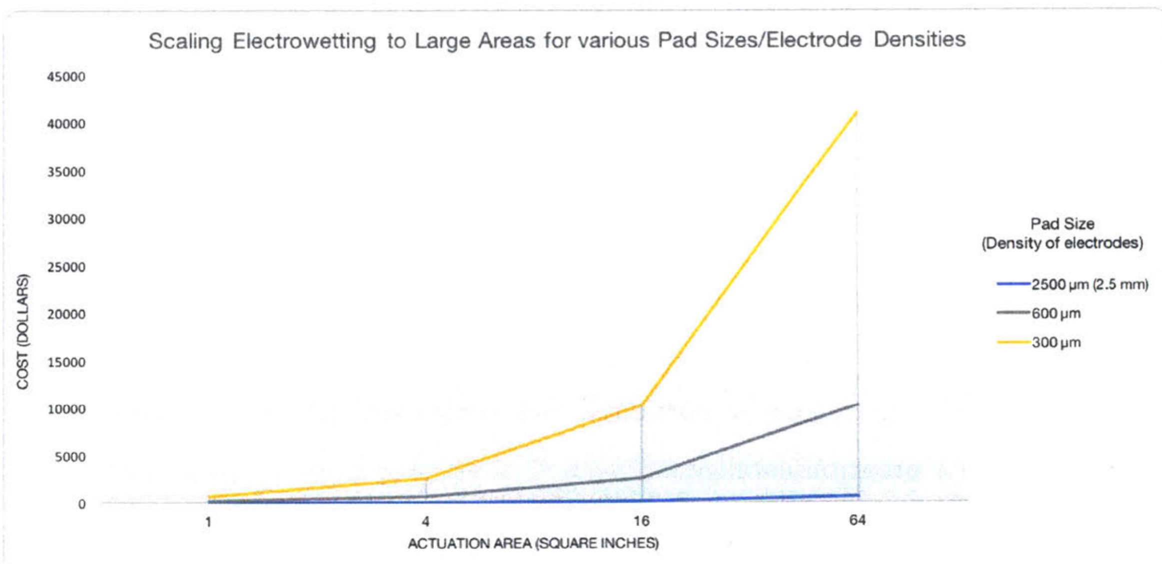

Figure 5-3: Scaling Electrowetting to Large Areas for various Pad Sizes.

As the size of the electrode is reduced, the size ratio increases. The number of driver ICs required for a given actuation area increases. As the electrodes approach the 100 μm limit, the number of driver ICs increase by two orders of magnitude. A 16 square inch grid with 2.5 mm electrodes (current DropletIO device) costs ~\$200. The same sized grid with 300 μm resolution requires 1024 discrete driver ICs and costs ~\$ 10,000 (see Fig. 5-3).

5.3.2 Scaling to Dense Arrays

The present architecture with discrete external drivers, scales economically to large areas when the size of the electrodes are of the order of a millimeter. The architecture will not scale to larger areas cost effectively for dense electrode arrays (sub-millimeter electrodes); see Fig. 5-3. Scaling electrowetting architecture to dense arrays involves complex routing, interconnects and control electronics. The current DropletIO architecture involves the use of a large number of discrete components; this is a cumbersome integration process and economically unviable. When scaling to dense arrays, electrowetting suffers from the same problem as electronics – the *tyranny of numbers.*

The electronics industry has solved similar scaling problems in the displays and data storage. One particularly relevant approach is a multiplexing scheme referred to as *active matrix drive* [77]. In active matrix driving, each pixel has a capacitor that maintains state and a transistor that switches states. Similar approaches can be applied to solve the *tyranny of numbers* problem when scaling electrowetting to dense arrays.

5.4 Digital Millifluidics

Historically automated liquid handling has relied on pressure differentials to transport liquid. In the 1990s, a new method for fluid handling called *microfluidics* was developed following DARPA's push for field-deployable liquid handling systems. Microfluidics is the science and art of handling small volume fluids. Small volume fluid handling can be classified as nanofluidics, microfluidics or millifluidics (see Fig. 5-4), as the boundary is not defined clearly.

Millifluidics deals with fluid volumes in the microliter to milliliter volume fluids (Fig. 5-4). By discretizing fluids into blobs it is possible to manipulate them on an electrowetting platform like DropletIO. I have demonstrated the possibility of performing the following fluidic operations with milliliter volumes: transporting, merging, mixing and splitting. I propose a new direction in handling milliliter fluids called *digital millifluidics.*

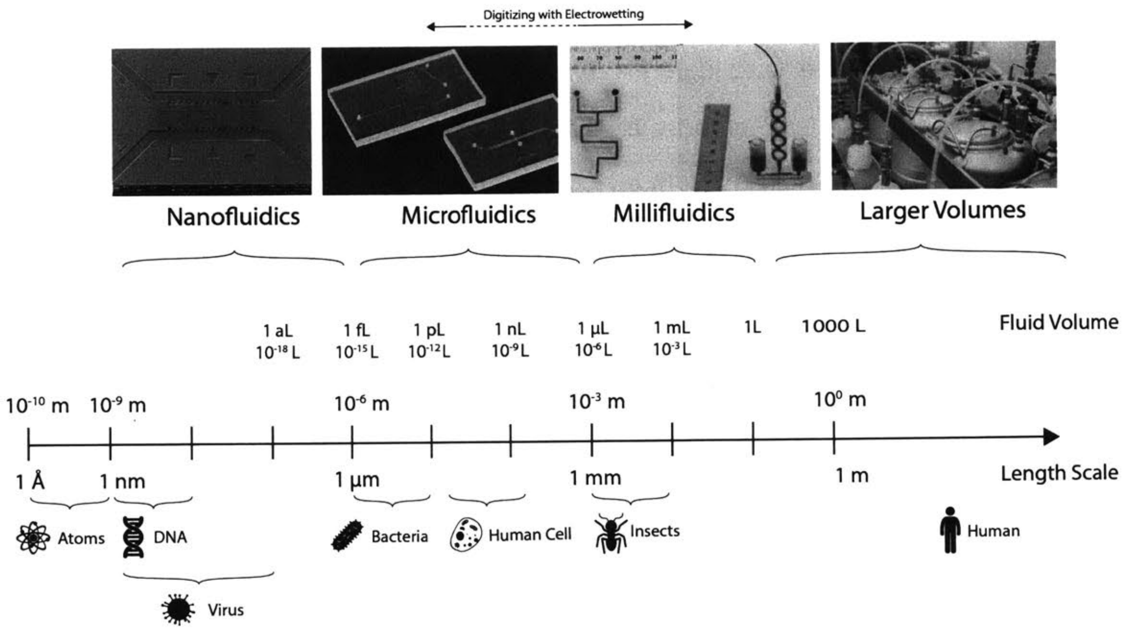

Figure 5-4: Digitizing Millifluidics.

Liquid handling devices in pharmaceuticals and gene synthesis require multiscale fluid handling ability. The state-of-the art systems are almost entirely pressure driven systems; these systems use valves and tubes of different sizes to transition from millifluidics to microfluidics. The lack of integration makes these systems cumbersome, expensive and unreliable. The DropletIO platform can solve this by being able to perform microfluidics and millifluidics digitally in a single system. Digital fluidics is more robust, scalable, and economical. Furthermore, the development of digital fluidics enables a number of additional applications in microbiology (Ex: Automated Cell Cultures), nanomaterials and chemical synthesis.

Chapter 6

Technical Evaluation

In this chapter, I provide some of the preliminary results of evaluation of the platform for volume of droplet that can be manipulated, velocity of motion, sensing accuracy, effect of gravity and time taken for homogeneous mixing. The evaluation was carried out under the following condition: freshly applied Parafilm and Silicone Oil with deionized water at room temperature in an open environment.

6.1 Droplet Volume

I observed through experiments that for a consist droplet motion, it is desirable to have the droplet extend at least 4 electrodes (2X2). To evaluate motion of various droplet sizes, I deactivate two electrodes (1X2) and activate two adjacent ones which advances a droplet by one electrode length. The electrodes were switched at 2Hz, giving the droplets sufficient time to advance. In 500 trials, a droplet of volume $10\mu l$ to $1000\mu l$ succeeded moving 100% of the time. This is clearly within the regime of millifluidics. Droplets of volume lesser than $10\mu l$ succeeded 50% of the time in 500 trials. Droplets larger than $1000\mu l$ exceeded the width of the available actuation area and hence could not be evaluated. In addition, I also noticed that as the droplet size grew, gravity started to have an effect on the motion of the droplet. For example, a $300\mu l$ droplet would roll away from the board at 1 degree tilt.

6.2 Effects of gravity and Sliding Angle

In electrowetting, for droplets sandwiched between two plates, capillary forces dominate gravity and usually a droplet sliding away is not an issue. However, in DropletIO I chose to have droplets on an open surface, and, at macro-scale a dominant force on physical objects is gravity. To evaluate the effect of gravity I put a droplet on electrowetting surface to find out the minimal angle at which a droplet starts to slide.

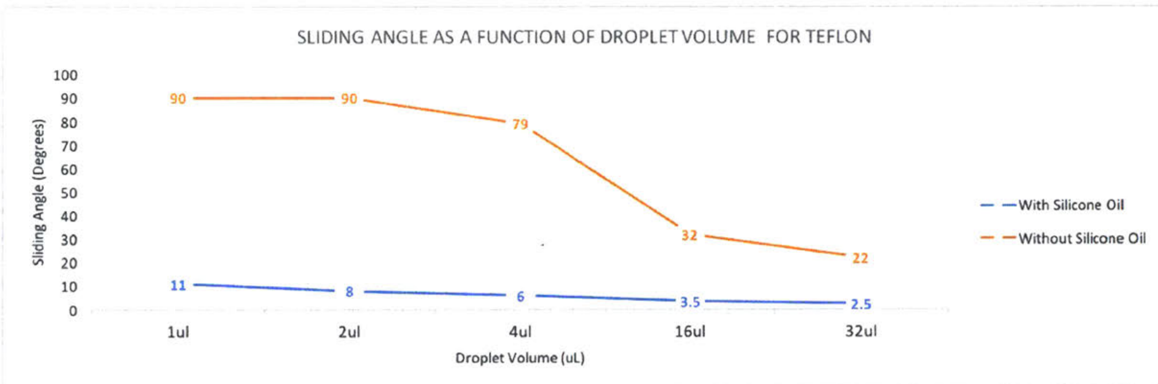

Figure 6-1: Sliding Angle as a function of droplet volume for Teflon Film.

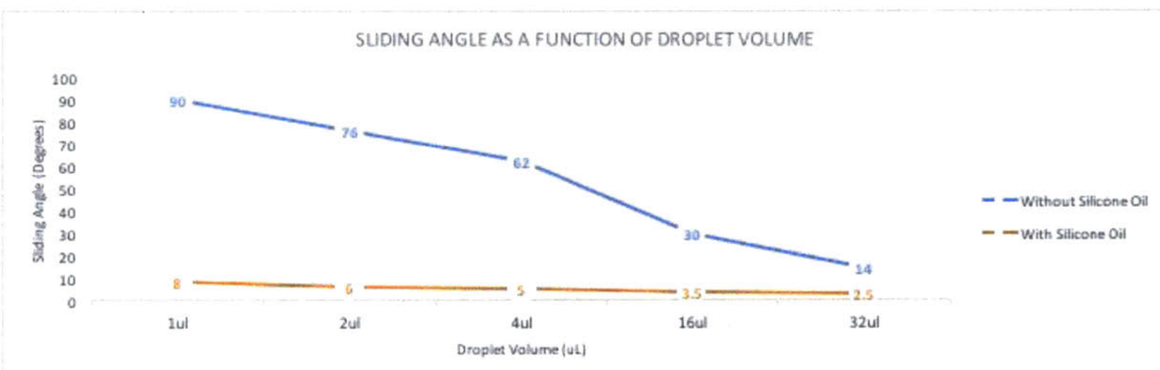

Figure 6-2: Sliding Angle as a function of droplet volume for Parafilm.

I evaluated the sliding angle on two different dielectric films — Parafilm and Teflon. For each film the sliding angle test was performed under the two conditions – with and without Silicone Oil on the top surface. As seen in Figure.6-1 and Figure.6-2 gravity seems to have a pronounced effect on larger volume droplets. And addition of Silicone Oil reduces the sliding angle significantly and this makes it possible for electrowetting forces to actuate a droplet.

6.3 Mixing

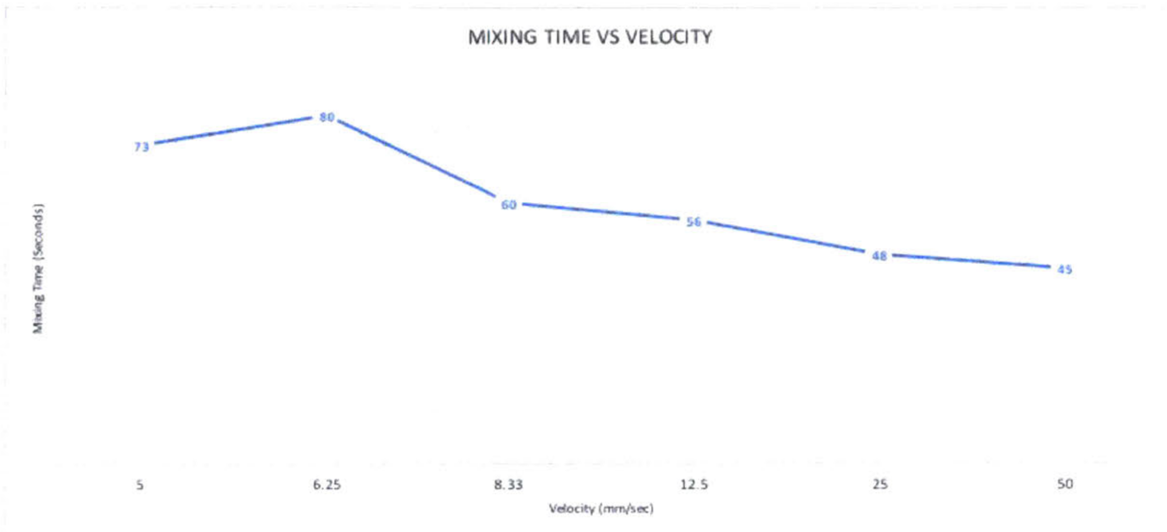

Figure 6-3: Mixing Time as a function of velocity of droplets.

Mixing is an important operation used in microfluidics; to prepare input samples for analysis, to dilute concentrated substances, and to control reagent volumes. Achieving homogeneous mixture depends on the volume of the droplet, the velocity at which two droplets collide, the contents and the operation temperature. I noticed under a high-speed camera that collision of two droplets create surface waves and the extent of agitation and mixing is proportional to collision speeds and size of the droplets. I performed a preliminary test to understand the relationship between velocity of droplets and mixing time for a $100\mu l$ droplet volume at room temperature. As seen in Fig. 6-3, the time required for mixing reduces with increased velocity.

6.4 Evaporation

A droplet on an open surface tends to evaporate faster than one enclosed in capillaries. Figure. 6-4 shows the time taken for a droplet to fully evaporate when placed on

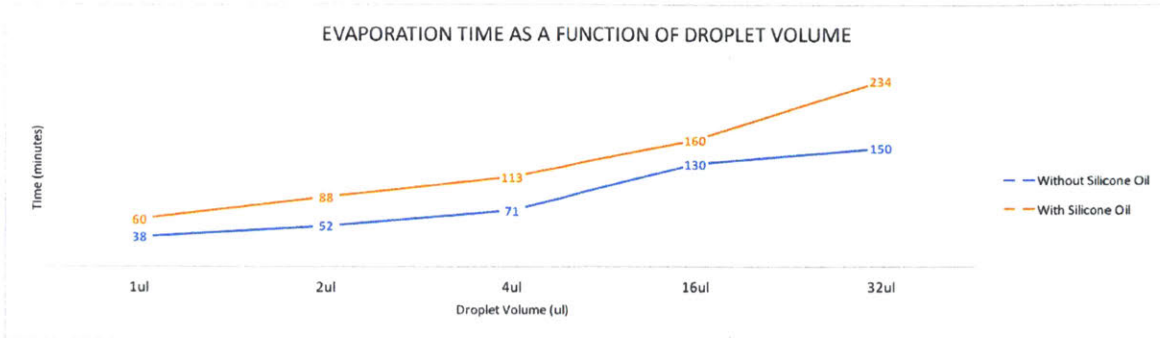

Figure 6-4: Evaporation time as a function of droplet volume.

Parafilm. It is important to notice that the rate of evaporation is reduced when Silicone Oil is applied. Air currents interacting with a droplet and hence evaporation can be reduced by enclosing the electrowetting platform. Further investigation on evaporation is left as future work.

6.5 Capacitive sensing

The capacitive sensors scan each electrode at 3kHz. The 16 bit resolution on the signal can differentiate droplet diameter difference of 0.5mm and has sufficient range to detect a hand. When an electrode is sensing, adjacent electrodes were grounded to prevent coupling between electrodes. Partial presence of a droplet on multiple pads is detected through individual signal levels.

6.6 Speed of Manipulation

For measuring droplet speeds I used the capacitive sensors which scan quicker (3kHz) than the fastest droplet transition between electrodes (50Hz). The speed increased proportionally to droplet size. The speed is independent of electrode size for a fixed actuation voltage. A maximum of 125 mm/s was achieved for droplets volumes $10\mu l$ to $1000\mu l$.

Chapter 7

Interaction Design Space

7.1 Background

We encounter liquid material in the form of droplets in our everyday life, while in rain, while cooking, painting and other scenarios. In these cases, not only do droplets have utility but also provide added context through sensations of touch and vision. Often the touch sensation itself is a multi-sensory experience giving the feeling of flow, viscosity and temperature. Tangible User Interfaces (TUIs) [21] such as Illuminating Clay [54] and Sandscape [74] showed how a user's familiarity to basic material forms such as sand and clay can be employed in computer interfaces. Building on the same principles, in this chapter of the thesis I explore how programmable droplets can be incorporated in interaction design.

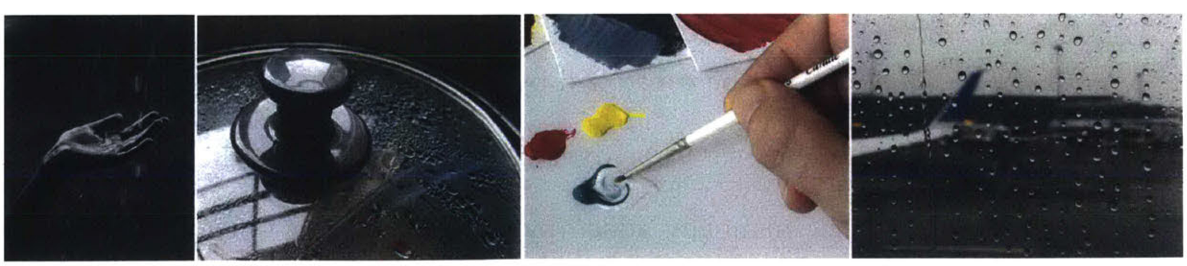

Figure 7-1: Droplets in everyday life.

In the context of artistic expression, liquid materials (water and oil) are a powerful medium. Water in the form of droplets has inspired poets, painters, philosophers and even scientists for centuries. More recently, artists have employed the aesthetics of moving droplets for animations [69] and kinetic installations. The rich set of dynamic operations and aesthetics provided by DropletIO system will enable new ways of expression. Rain droplets on a glass window invite one to touch and play; these playful interactions can be enriched with computational control of droplets. With droplets as a medium for dynamic artwork, play and interactivity, in the rest of the chapter I will elaborate on interaction primitives and the design space from a human interaction standpoint.

7.2 Physical Interaction with Liquid Matter in the form of Droplets

Researchers have argued for employing the user's understanding of naive physics in interaction design through the body's relationship with physical materials [26, 27]. DropletIO lets users interact with the moving droplets in various ways by utilizing their familiarity and physicality. Examples of physical interaction that the DropletIO platform provides are:

Touch – Droplets can be touched by the users' fingers in order to manipulate their position and shape .

Tilt – Droplet motions can be controlled by users tilting the interaction surface.

Blow – Droplets can be blown to be dynamically moved across the surface.

Add – Droplets can be manually added by users using tools such as pipettes or simply by hand.

Remove – Droplets can be removed by users, for example by wiping them off.

These interaction primitives are put to use in the example applications described later.

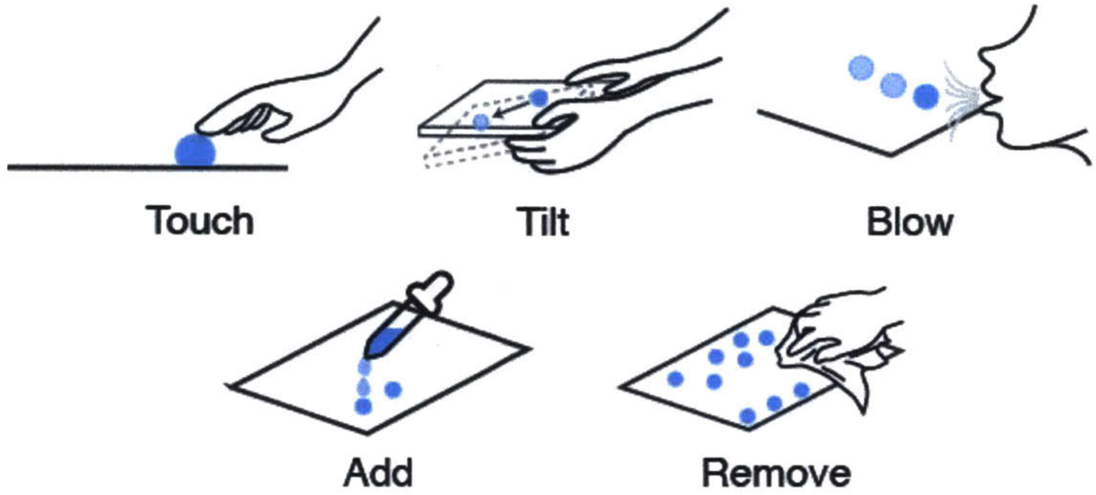

Figure 7-2: Examples of primitive interaction with physical droplets.

7.2.1 Touch

A user can directly touch a moving or a stationary droplet on the interaction surface; see Fig. 7-3. By touching a moving droplet a user can add constraints, for example, to guide it in an alternate path or impede it's motion entirely. For instance, a user can employ the touch interaction to add a constraint that stops an animation rendered on a DropletIO display. Removing the constraint can then restart the animation. Pushing a stationary droplet deforms it and the systems also recognizes this as a touch input through the droplet. This interaction can be used to detect the state of a dynamically rendered binary switch for example.

7.2.2 Tilt and Blow

Opposing gravity through computation is a concept that has been explored previously in HCI. For example ZeroN proposed the idea of a *anti-gravity space* [35], where the effects of gravity on a physical object is nullified with magnetic force field. While a user can *tilt* a DropletIO board to gravity steer a droplet (7-4), it is also possible to oppose or augment this user action with computer generated electric field. In

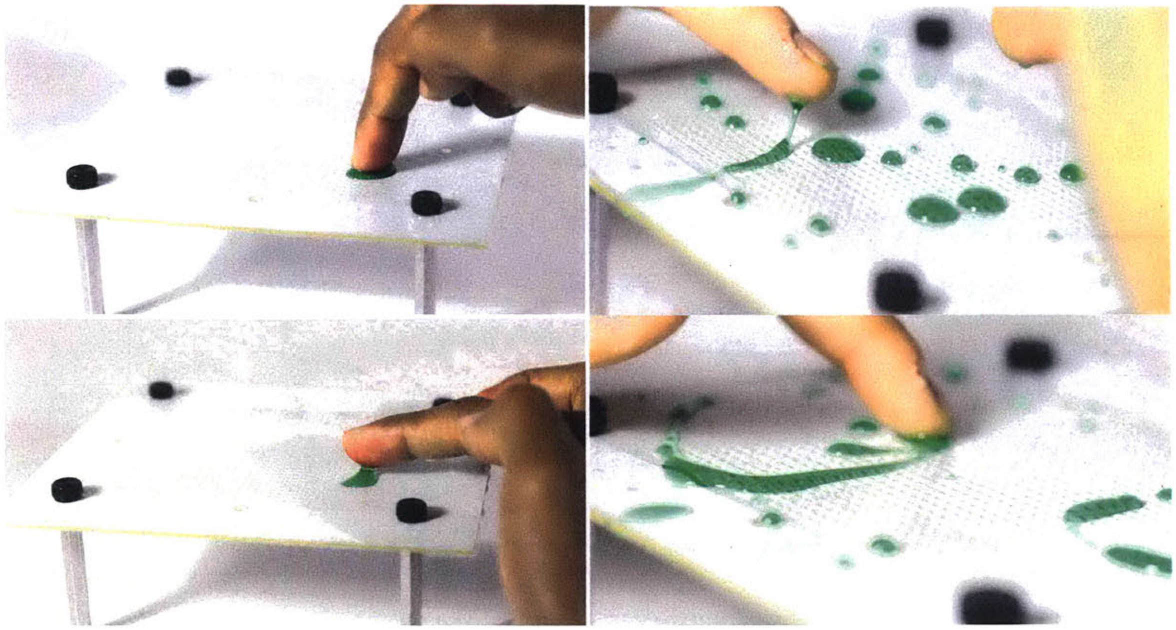

Figure 7-3: Interacting with droplets by touching, dragging and moving.

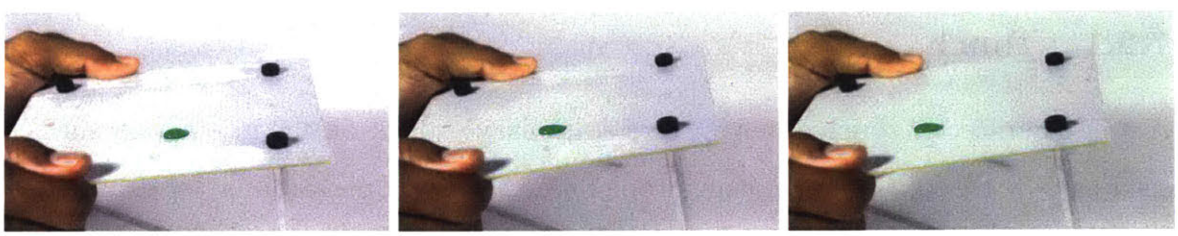

Figure 7-4: Tilt action to steer a droplet.

response to a user's *tilt* action, the system can respond to the user action with one of the following actions:

- nullify the effect of gravity by stopping the motion of a droplet or
- influence the path taken by the droplet through electric field, an extreme case would be a droplet climbing vertically

A droplet flowing down a tilted surface can also be programmed through the electric field to emulate fluids with different viscosity. Although here the actual viscosity of the material is not changing, a user can be made to perceive difference in viscosity by regulating the flow behavior.

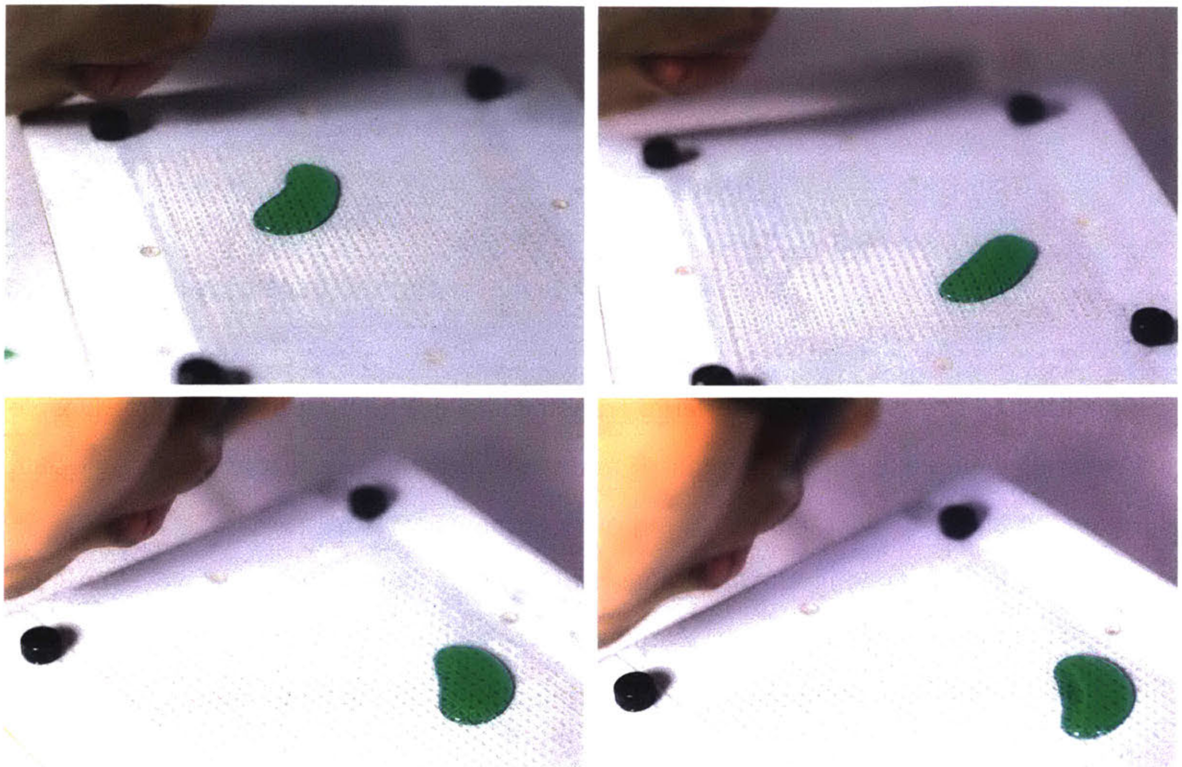

Figure 7-5: Top: Moving a droplet through blow operation. Bottom: Morphing a droplet through blow operation.

A user blowing a droplet can also affect the movement of a droplet or even morph a droplet to various shapes.

7.2.3 Add and Remove

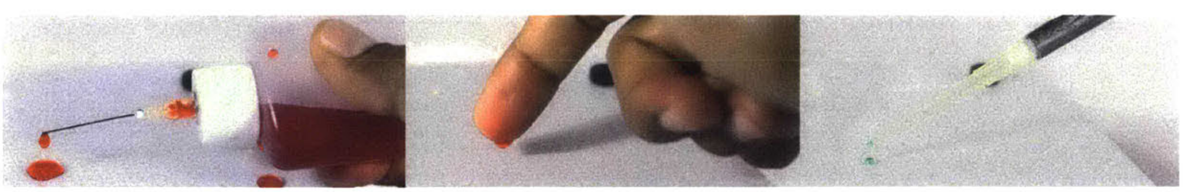

Figure 7-6: Adding droplets to the interaction surface.

Droplets can be added to the system directly by hand or through tools like pipettes or droppers (Fig. 7-6). These additions can be detected through capacitance sensing. This offers the ability for one to add commonly used fluids in our lives. Materials

Figure 7-7: Removing droplets from the interaction surface.

thus added to the system can undergo transformation under the influence of DropletIO system. Similarly, one can remove material from the DropletIO system through familiar interactions such as by wiping or washing away (Fig. 7-7).

Adding and removing physical material on to a computer interface shows the possibility of being able to make a seamless transition between static physical material in the real world and programmable materials under the influence of computation.

7.3 Design Space

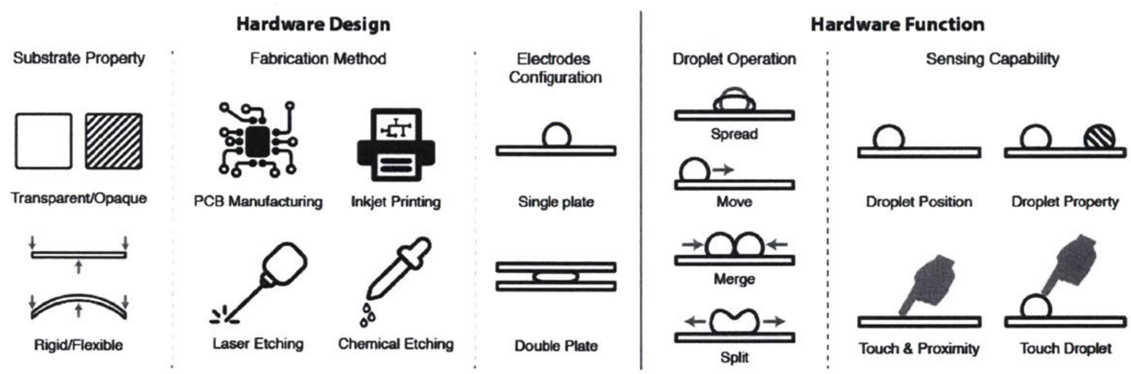

Figure 7-8: DropletIO Device Design Space.

7.3.1 Droplet Actuation Operations

Simple Operations

The operating principles section discusses droplet actuation operations: *moving*, *merging*, *spreading*, and *splitting*. By utilizing these operations and combining their functionality, interaction designers can compose and animate droplets. In this thesis, the interactive examples prototyped demonstrate the use of simple droplet actuation operation. The complex operations explained below are left for future exploration.

Complex Operations

Sequencing a set of simple operations or when a droplet interacts with a material other than liquid, a few different complex operations described below become possible.

- *Morph* - by activating electrodes in various patterns a droplet or even a blob of fluid can be morphed to various shapes. The morphing behavior of droplets can also be used in tunable optics, for example to change focus or even dynamic beam steering.

- *Mix* - merging two droplets does not always result in complete mixing. By moving a droplet back and forth or by stretching it across multiple electrodes through the *spread* operation, a droplet can be agitated to achieve proper *mixing.*

- *Chemical reaction* - droplets carrying biological materials can serve as tiny bioreactors and droplets with chemical entities can initiate chemical reactions. While these are obvious applications in digital microfluidics, they have potential applications in HCI as well.

- *Inter-material Interaction* - liquid material when interacting with other material produces a physical property change in the material through capillary forces and surface tension. These interactions hint at possible exploration within the umbrella of inter-material interaction, which was first introduced by Follmer et al. [14]

7.3.2 Programmable Properties and Dynamic Affordances

In relationship to perceived and real affordances [15], Gibson listed a number of physical parameters of an UI element, namely size, shape, color, volume, and motion.

Shape changing interfaces have shown how one can create dynamic affordances associated with parameters such as size, orientation, texture, density, stiffness. Follmer et al. [14] were one of the very first to talk about rendering dynamic affordance for interaction design. However, these were limited to the properties of solid rigid bodies. With the previously mentioned programmable properties, DropletIO enables rendering a range of other dynamic affordances possible only with liquid material.

Programmatically merging and mixing of droplets with different compositions produce various desirable physical properties. These properties can be perceived through vision, smell and touch. For example, mixing yellow and blue droplets to produce green droplets. Similarly, mixing two droplets of vinegar and baking soda give rise to an exothermic reaction thus providing an ability to programatically change the temperature purely through material composition. The approach can be applied to other properties namely, volume, color, transparency, pH, viscosity, biological cell concentration, conductivity and many other properties.

7.3.3 Sensing and IO coincidence

DropletIO system has several sensing capabilities to detect droplets and human touch events for interaction with moving droplets. The system can detect the position of droplets within the interaction space, partial or complete presence on an electrode and the size of a blob or a droplet. The capacitive sensing technique enables the system to detect direct touch as well as proximity above the interaction surface. By combining several sensing capabilities, the system can also detect which droplet is being touched by a user.

It is important to note that both actuation and sensing of droplets is done through capacitively coupled droplets, thus establishing IO coincidence [26].

Chapter 8

Interactive Applications

To demonstrate the versatility of utilizing droplets in a range of applications, I reimagine some of our encounters with fluids in daily life. These applications show how droplets can be used in dynamic information displays, for precise fluid mixing, games and kinetic art.

8.1 Example Applications

8.1.1 Interactive Information Display

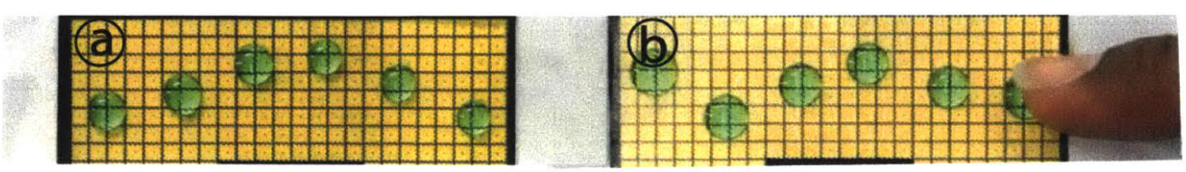

Figure 8-1: Wave simulation on an interactive display.(a) Droplets dynamically rendering a wave.(b) User inputs constraints through touch.

Programmable droplets can render information by moving on the DropletIO surface. Figure 8-1 shows how multiple droplets act as pixels to form a sine wave. A user can add constraints to the simulation through touch input. For instance through a simple touch gesture recognized by the system, the animation can be initiated and stopped.

The transient nature of the droplets provides unique affordances, allowing for interaction by *touching, adding and removing* droplets. This way, the user can for instance control the level of fidelity at which information is displayed, or add new parameters to a simulation. The *spread* primitive can also be used in the information display, for instance to grab the attention of a user. Interacting with the moving droplets visually and through touch evokes a multi-sensory experience.

8.1.2 Mixing Colors

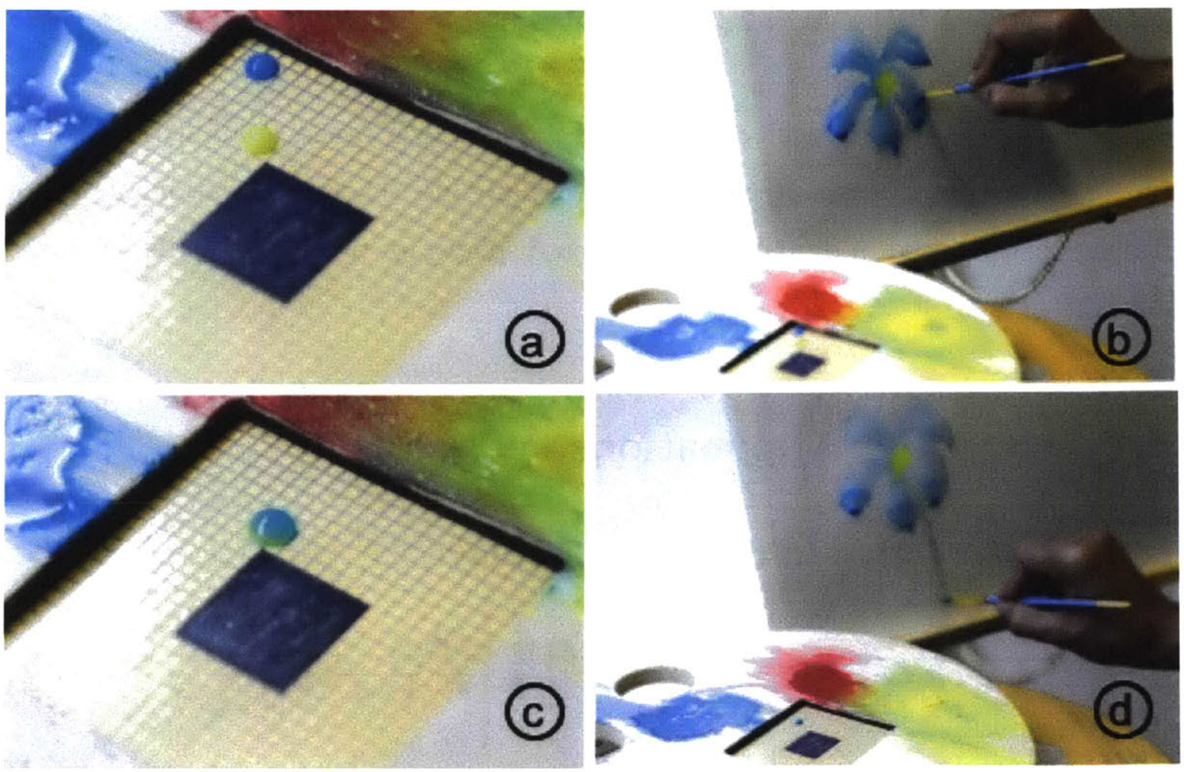

Figure 8-2: (a) Paint droplets on DropletIO palette. (b) An artist painting a flower. (c) Green formed on DropletIO platform by automatically mixing blue and yellow droplets. (d) Artist continues painting the stem with green.

The compact form factor of the DropletIO device allows integration into a physical color palette for automatically and precisely mixing colors. Artists can create physical colored paint from a digital palette. Fig. 8-2 shows a use case, where an artist starts by painting a flower with blue and yellow colors. The application proposes a green color, and the DropletIO palette automatically creates the color by mixing droplets.

A droplet-wise control of fluids on our platform facilitates such repetitive mixing of colors with precision.

In contrast to traditional microfluidic electrowetting platform, DropletIO platform was engineered to be a 2D grid that can manipulate larger droplets on an open surface. Droplets appropriate for a regular paint brushes can be *dispensed* from a larger pool with a *split* operation. A series of mixing operations can produce a palette of colors from a fundamental set of Cyan, Magenta and Yellow. However, the range of achievable colors is limited by the smallest droplet that can be created and the number of mixing operations.

8.1.3 Droplet Games

I prototyped a game to leverage the familiarity of physical droplet manipulation with gravity. The user and the computer can simultaneously manipulate the same droplet through different means. The user controls the droplet by tilting the platform in different directions, while the computer alters the droplet's motion by changing the wettability of the surface and guiding its motion.

A user steers a large red droplet (see Fig. 8-3), to absorb other small characters. The primary character is the large red droplet; characters are represented through droplets, with the primary character being larger than others. A user tilts the DropletIO-based console to steer the main character to capture other characters (Fig. 8-3 a) and grow in size. As the smaller droplets are consumed the larger character also embodies all the physical properties of the smaller ones. The user is challenged by the computer controlled smaller characters by getting farther away (Fig. 8-3 b).

Tilting the landscape through tilt control is a physical action that is easy to learn and illustrates the effects of gravity. The game could serve not only for entertainment purposes, but also as an educational tool, illustrating the effect of gravity or the rheological properties of fluids.

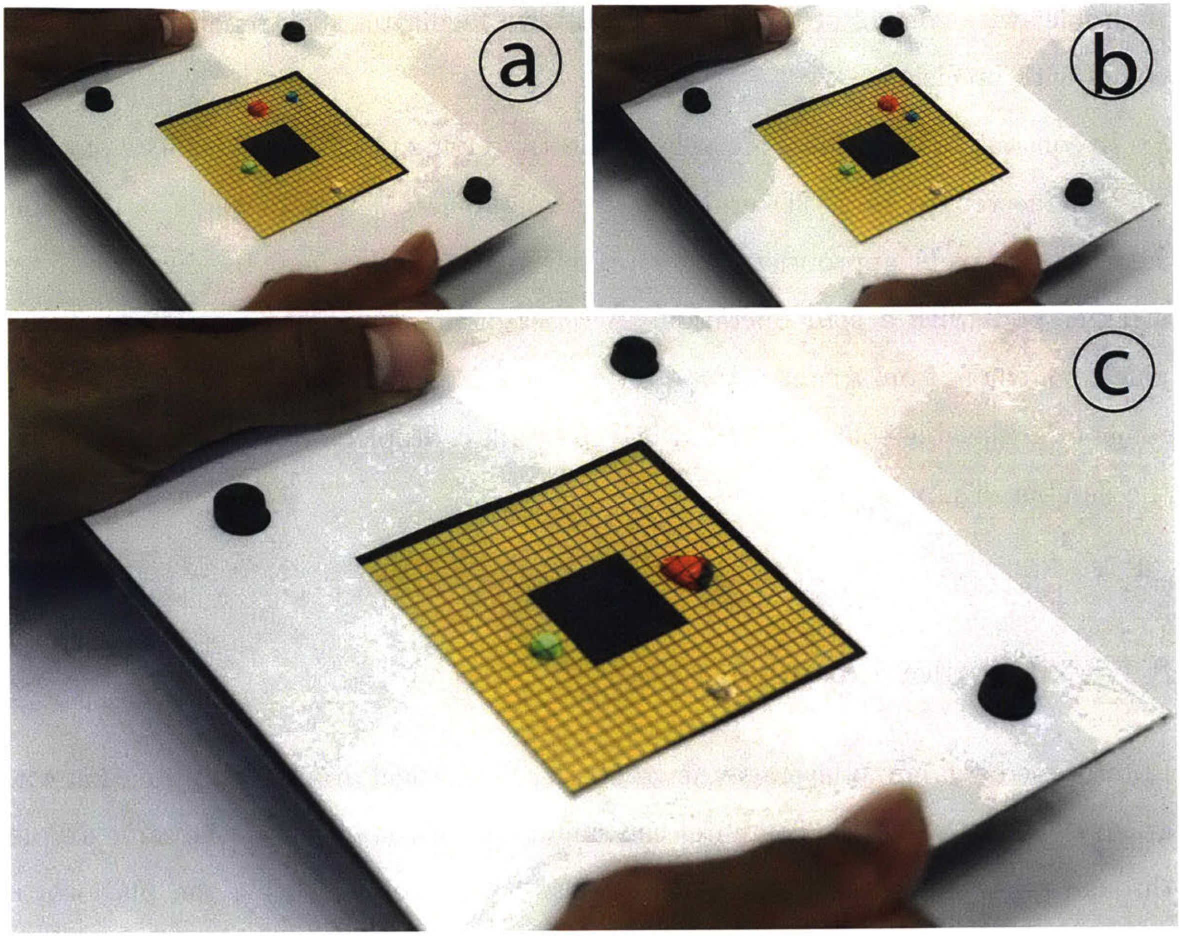

Figure 8-3: Interactive game. (a) A user controlling a red droplet by tilting the device. (b) Small droplets moving away from the red droplet. (c) Red droplet prey on a green droplet.

8.1.4 Aesthetics of droplets in Kinetic Art

Water is essential to all life, and this relationship has intensely influenced many artists to use it as a medium for expression. The aesthetics of a droplet and the subtlety in its motion has evoked people's emotions as many kinetic artists have explored [28, 49, 57]. Inspired by the aesthetics of droplets in motion, I choreographed a scenario around two dancing droplets. In another instance, I appropriated the life-like motion of large blob for narrating the story of a creature roaming the world looking for food (Fig. 8-4). I believe that these application examples demonstrate how DropletIO enable new artistic tools for creative expression.

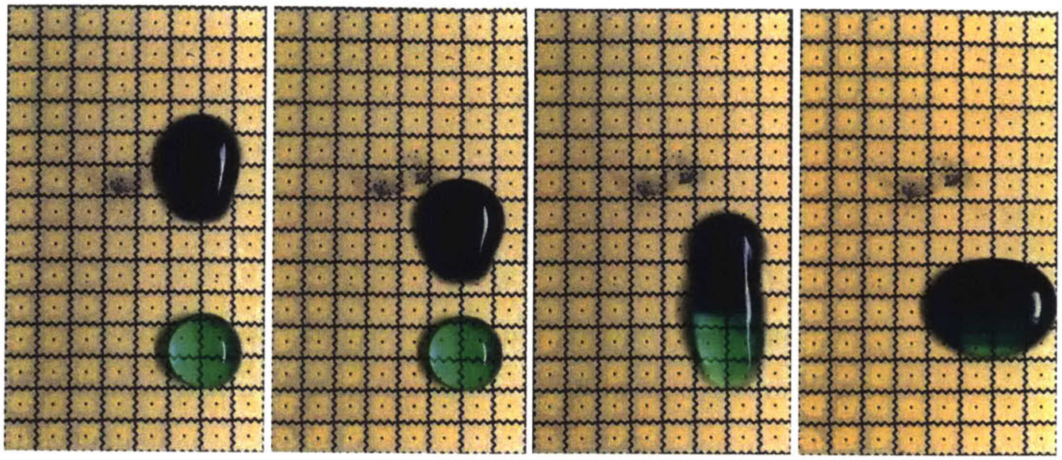

Figure 8-4: Life-like behavior of droplets.

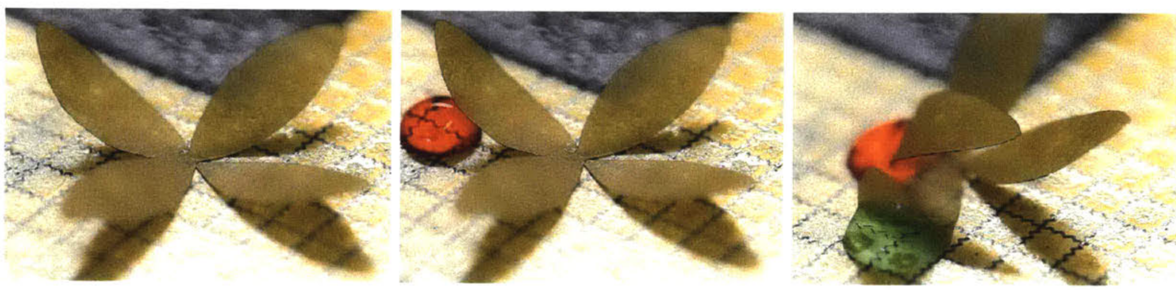

Figure 8-5: Activating a flower. (a) Flower made by lasercutting a piece of paper. (b) Droplet delivery to activate flower. (c) Flower petals flourishing by absorbing water.

8.1.5 Controlled Paper Folding

In HCI, thin film folding has been explored for shape changing interfaces [21, 79] and self transforming paper pop-up cards [80]. However, in these approaches, the folding material requires special processes to induce the actuation. Here, I show a simple technique to fold thin films, which requires no modification to the material. I take advantage of the capillarity of wax paper to create programmable folding at centimeter scale. The sequence, in which the droplets wet different surfaces of the paper, determines the folding behavior.

To demonstrate this idea, I made a flower-like structure out of wax paper. The sequential blooming behavior was translated to a sequence of droplet deliveries onto each petal. By carefully timing the delivery, various blooming behaviors can be programmatically achieved as in Fig. 8-5. Such a behavior is possible only on DropletIO because of the following – the low surface energy of the hydrophobic surface and programmatic control over sequential delivery of droplets. The low surface energy reduces the attraction between the petal and the solid surface, allowing the capillary forces to dominate.

Water can weaken paper by wetting and has been used for computationally fabricating origami structures [18]. With the proposed approach in DropletIO, folding behavior can be induced in flat sheet material with applications in manufacturing and packaging.

Chapter 9

Limitations

In this chapter, some of the technical limitations of the DropletIO system are briefly discussed.

9.1 Dielectric Film and Hydrophobic Coating

The dielectric film and hydrophobic coating for electrowetting have tight constraints on uniformity in thickness. Standard PCB manufacturing process introduces significantly large surface roughness that makes it challenging to achieve a uniformly thin dielectric and hydrophobic coating. Any variation in the thickness of dielectric material results in variable actuation force and hence unreliable droplet motion. The thickness also affects the measured capacitance that is used for feedback.

Although commodity materials for dielectric film, Saran Wrap and Parafilm are easily available, processing them for a uniformly thick layer on the PCB electrodes is challenging. A method that is typically used in electrowetting to achieve uniformity is to pre-stretch the film to its yield point, prior to its application on to the electrodes. However, stretching the film does not provide uniform thickness over larger areas and over longer time period. For the hydrophobic coating, a thin layer of Silicone oil was manually applied with a foam brush or gloved fingers; to make the procedure repeatable procedure, I built a custom spin coating device for applying thin film coating directly on to the DropletIO boards. An alternate approach to achieve robust dielectric layer and hydrophobic coating is to use a combination of advanced thin film fabrication methods such as vapor deposition, spraying, dip-coating and spin coating, which is reserved for future work.

9.2 Effect of Droplet, Human Touch and Dust on Hydrophobic Coating

In DropletIO prototypes, Silicone Oil on the dielectric film provides a hydrophobic surface by reducing the surface energy. A droplet accumulates a layers of Silicone Oil around itself as it maneuvered, resulting in gradual loss of hydrophobicity. Similarly, any human touch removes small qunatities of Silicone Oil from the surface and also results in contamination of the hydrophobic surface with tiny particulate matter.

Prolonged usage of the DropletIO device with exposed surface for fluid manipulation can result in accumulation of dust and affect the device performance. Small amounts of particulate material on the surface can sufficiently modify the hydrophobic surface to prevent a droplet from making a smooth transition or prevent a droplet from moving. Although dust can be removed by washing, the device may not function as well as a freshly prepared layer of dielectric film and hydrophobic coating.

9.3 High Actuation Voltage

DropletIO devices require voltages as high as 275 V DC to actuate the droplets. The actuation voltage is primarily a function of the dielectric constant and the thickness of the dielectric film on the electrodes [45]. With alternate materials and coating methods, it is possible to increase dielectric constant and make thinner dielectric films to bring down the actuation voltages [39].

9.4 Safety

During the initial development, I have occasionally felt minor irritation when in direct contact with high voltage (275 V DC). Later devices were electrically insulated for additional safety. As demonstrated in the examples, I have been operating the device with direct human touch. Although higher voltages can be detrimental, the charge on the electrodes ($5nC$) delivered to a human from the system is very minimal. The National Electrical Code (NFPA 70) in the United States classifies DC voltages less than 50 V to be low voltage. It is desirable to lower the actuation voltage for a safer operation from an human-computer interaction standpoint. Literature has shown that voltages as low as 15 V can actuate droplets [45].

Chapter 10

Future work

In this chapter, I will go over future work that grows out of this thesis. I briefly talk about improving the process of fabricating electrowetting arrays and how it enables applications in multiple fields.

10.1 Advancing Electrowetting

Further work needs to be done on robust dielectric film and hydrophobic surface in order to make the platform suitable for real world applications. DropletIO electrowetting arrays were fabricated with PCB manufacturing, a mature and inexpensive fabrication process. I am exploring ways to engineer thin film ($1mu$m) that is inherently hydrophobic (through surface texture) that can be applied to electrodes after PCB fabrication. An alternate approach I am investigating is the integration of dielectric/hydrophobic application in to the PCB manufacturing process itself; for example the solder mask applied in a standard PCB manufacturing process can be as thin as 0.3 mils (7.5 μm). Once the surface is functionalized to reduce surface energy, by using the solder mask as a dielectric, it will become an integrated film on the electrode for smooth droplet motion.

Scaling electrowetting to dense arrays from discrete components is not economical. Similar problems have been solved in the displays and data storage industry. Similar processes can be adopted to scale electrowetting in a cost effective manner (see Scaling

Electrowetting Chapter for details).

10.2 Droplets for Future Interaction Design

10.2.1 Van Gogh Palette

"I often think that the night is more alive and more richly colored than the day."

—Vincent Van Gogh

The essence of an artist's life and craft is embodied in the brush strokes and the color palette. For example, Vincent Van Gogh, a 19th century painter is known for bright, lavish colors with visible brush strokes. Art historians argue that the the visible strokes reflected the mental illness Vincent was suffering from. A closer look at Van Gogh's work reveals that the range of colors in his paintings are tightly coupled to events in his life.

Figure 10-1: Vincent Van Gogh's painting. (a) Potato Eaters (1885). (b)Vase with Red Poppies (1886). (c) The Old Mill (1888). Van Gogh expanded his palettes from dark earthy colors to Blue and Green to brighter yellow through his life.

Vincent's early work during 1885 primarily consisted of shades of dark brown (dull earthy tones) [68]. This was very well suited for his subjects – miners, weavers and peasant farmers (see Fig. 10-1 (a)). Later, when he was criticized by his brother Theo for not having brighter colors (like in Impressionist paintings), his palette expanded to include Carmine, Cobalt Blue and Emerald Green (Fig. 10-1(b)). Van Gogh's work towards to the end of his life uses opulent yellow, ultramarine and mauve capturing the bright landscape of the city of Arles in France (Fig. 10-1(c)).

By pointing a camera at an artist's work or with an image of the work as an input, it is possible to extract the range of colors used in a painting. DropletIO can then automatically generate these colors to recreate an artist's palette with his/her value system. Using a dynamic color palette with dancing droplets for color mixing can depict elements of evolution of the art process of an artist.

10.2.2 Multi-sensory Interactions and Shape Transformation

Programmable droplets enable a rich interaction design space with readily available, water-based droplets. Visual and touch sensations arising from droplets in motion demonstrate the use of droplets for multi-sensory experiences. The droplets in the information display are not only visually appealing when in motion, but also excite the skin when a user wipes them, drags them along or manipulate them through other touch gestures. Within the scope of this thesis I have demonstrated a few examples demonstrating these multi-sensory experiences. Future examples could include a rich set of expressive behaviors through multi-sensory interactions and shape transformations.

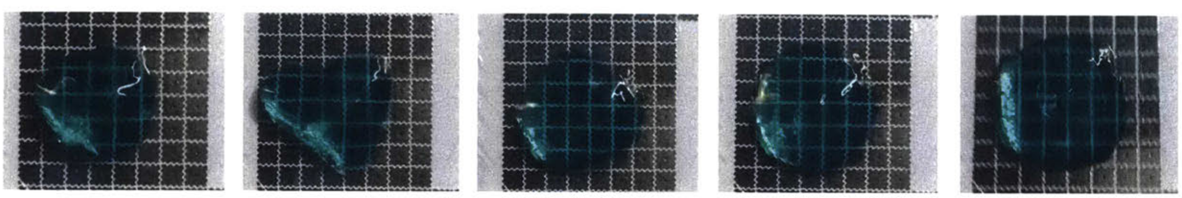

Figure 10-2: Transformations through various electrode activation pattern.

Recent experiments with actuation patterns demonstrated the possibility of using droplets for various kinds of shape transformations; see Fig. 10-2. Activating electrodes in specific patterns can produce a range of shape transformation. Furthermore, by rapidly changing the activation pattern, a droplet can rapidly transform, exhibiting life-like behavior. These behaviors expand the range of expressive patterns and shows a promising direction within the droplet based display application space.

10.2.3 Interactions based on Ambient physical materials

The interactive applications demonstrated in this thesis show how droplets can be explicitly added, modified, and removed by a user. However, the DropletIO system could also enable more ambient and implicit interactions, where droplets already present in the users environment are harnessed and manipulated by the device. Such *ambient physical materials* add a new dimension to common everyday objects like windows, cups, lids, and umbrellas.

10.3 Wet Lab in a Box

Unlike pressure driven liquid handling systems, DropletIO electrowetting platform does not require tubes, valves and pumps. The absence of mechanical parts and use of solid state electronics, makes DropletIO a compact and portable system. The programmable nature of the device allows for executing complex liquid handling protocols for bio-chemical synthesis/analysis. Such a compact programmable system for advanced fluidic operations can be carried in backpack.

Integrating the DropletIO system with lab tools such as a thermo-cycler for PCR (polymerase chain reaction) becomes a mobile lab that can synthesize and clone DNA. Similarly, with DropletIO as a liquid handling tool, and a range of other detection and analysis tools, bio-chemical wet labs can be fit in a box. Such wet-lab-in-a-box will sit on desktops, similar to personalized 3D printers, bringing the ability to programatically execute biological experiments on the go.

10.4 Programmable Chemistry

In the world of chemistry, droplet based digital microfluidics (DMF) with Electrowetting on dielectric (EWOD) has applications spanning across automated bio-chemical assays, library preparation for chemical analysis/synthesis, next-gen sequencing and point-of-care diagnostics. Despite massive effort in the reserach community, the deployment of EWOD based systems is limited by cost effective scalability. At present, current electrowetting systems can be leveraged for automated fluid handling in laboratories, pharmaceutical and drug industry. This requires the integration of the EWOD system with already existing lab automation infrastructure. However, there is a significant potential in the future for miniaturization on the picoliter scale for single cell analysis and single molecule manipulation. In the following section I will briefly touch upon how large area electrowetting array like DropletIO have immediate applications and also project towards future research applications benefiting from miniaturization.

10.4.1 Parallelization of Bio-Chemical Experimentation

Many bio-chemical application in industry and research labs require high throughput liquid handling systems. Multi-step bio-chemical assays in pharmaceutical industry and library preparation in next-gen DNA sequencers are two specific applications that would benefit from an automated high throughput liquid handler.

In most DMF devices, electrodes are arranged linearly, forcing multiple droplets to share the same path. This structure limits the number of droplets that can be manipulated simultaneously. Often, these devices also use a common drive signal to activate multiple electrode which limits the types of droplet operations that can be performed simultaneously. For a DMF device to be effective it must be able to perform multiple operations on a large number of droplets in parallel. DropletIO provides a solution to these probelms by architecting a large 2D array with direct addressing on every electrode. The array provides arbitrary programmable path for droplets and various droplet operations can be performed simultaneously. DropletIO's ability to actuate and sense individual droplets on every electrodes makes it a platform suitable for parallelized droplet microfluidics.

10.4.2 High Throughput Screening with Pipetting Robots

Pipetting robots and 96 well plates is the accepted standard for automation in the pharmaceutical and drug industry. Combining robotic infrastructure with DMF devices capable of precision high-speed droplet manipulation can significantly impact high throughput screening (HTS) or massively parallel analysis in drug manufacturing.

Traditionally, DMF devices have always sandwiched droplets between two plates; adding and retrieving samples is cumbersome. Although droplet manipulation on open surface DMF devices have been demonstrated, such devices have never been scaled to a larger array before DropletIO. Open surface DMF devices have the advantage of easy addition/removal of droplets and integrate well with pipetting robots for high throughput systems in industry.

10.4.3 DNA synthesis: Novel Construction Methods and Miniaturization

In the past decade, our ability to sequence DNA has rapidly advanced biological research and our understanding to life. We have also created many ways to make custom DNA molecules; including methods for *de novo* synthesis and cloning of DNA. Within gene synthesis, efforts are underway to increase throughput using microfluidics. Specifically, this becomes possible through parallelization, simplifying complex synthesis through automated liquid handling and miniaturization.

A recent paper [81] showcased how digital microfluidics (DMF) can be used for on-chip cell-free cloning of DNA constructs. The demonstration shows suitability of DMF for *de novo* DNA synthesis and cloning. DMF has not been widely explored in such applications; however, it has high potential for implementing and inventing novel methods for gene synthesis. Many of these methods have complex protocols and require redirecting of droplets programmatically. DMF provides a way to automate this process which is not possible manually or with pipetting robots.

10.4.4 Single Cell Manipulation

Studying cells and their expression under various conditions (Ex: response to a drug, gene expression) is common in biological research. In these studies, it is required to isolate individual cells. One reason for this is heterogeneity amongst cells. Another reason is to drive down the cost of experiments by being able to isolate a single cell or a few different cells in tiny droplet containers. DMF device like DropletIO have been shown to be suitable for manipulating cell suspensions [64, 52], miniaturization for smaller volume droplets is a research direction to consider.

10.5 Programmable Optofluidics

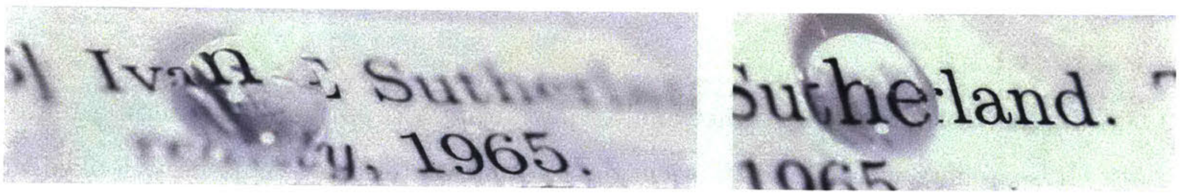

Figure 10-3: Droplets as dynamic reconfigurable lenses.

Droplets have the inherent ability to absorb, reflect, refract and scatter light. A droplet as a programmable object becomes interesting for it's tunable optical properties. For instance, by regulating the shape in an electric field a droplet can steer a beam of light in different directions. Programmability and dynamic reconfigurability is easily achievable on an electrowetting based array and hence finds applications in dynamic optofluidic devices.

Programmable Optofluidic devices have broad set of applications – laser radars, adaptive camouflage, electronic papers, optical tweezers, high-resolutions displays, structured and illumination microscopy. I have demonstrated the possibility of fabricating large electrowetting arrays and it's scalability. Subsequently, it should be possible to fabricate large arrays of micro-lenses, micro-mirrors, micro-prisms enabling a range of applications in tunable micro-optics.

10.6 Micro-robots in Programmable Force Fields

Fig. 10-4 shows a programmable platform for distributed manipulation of micro-scale objects through electric force field. The vision for such a system is a fully automated

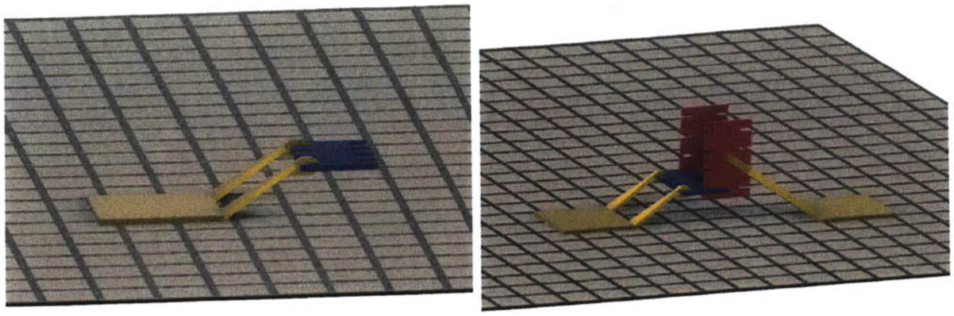

Figure 10-4: Render of Micro-robots assembling digital materials

micro-factory for assembling functional objects from a supply of raw building materials. Researchers working on fabrication of multi-material systems have looked at assembly of fully functional electromechanical objects from microscale discrete assembly blocks(Digital Materials [56]). Such systems that construct complex structures from large number of small parts is limited in assembly speed due to it's serial nature. One route to tackle this is parallelizing the assembly process. However, current assembly techniques rely on pick and place like operation with large machines, which do not scale if we aim for significant growth in assembly speed. I plan to scale the current electrowetting array, to a generic platform for precisely manipulating a range of dielectric materials. With such ability to manipulate microscale objects rapidly, without large machines, is one way to solve the long standing problem of limited throughput in directed assembly techniques.

The proposed system will allow for micron resolution manipulability on XY plane, rotation along Z-axis and limited actuation in Z-axis through levitation. Direct electrode addressability allows for simultaneous manipulation of multiple robots made of dielectric material such as Silicon dioxide. The ability to position objects precisely enables us to guide the motion and assemble parts programmatically. With a raw feedstock of discrete assembly blocks, this system will enable assembly of electromechanical systems, for example. I few challenges I plan to tackle to accomplish the proposed system include: range of materials that can be manipulated, designing micro grippers to carry parts, coordinating the arrival of parts, maintaining state machines for growth of objects, fine control over orientation and interaction between parts.

10.7 Directed Programmable Assembly

Droplets can carry various biological and chemical materials and as digital materials they can be programmed to assemble in to 3-dimensional multi-material structures. For the proposed application, inverted electrowetting arrays transport pico-liter droplets, precisely organize them on a 2D plane, which can then be deposited simultaneously as a single layer. The parallel nature of this method of multi-material 3-dimensional assembly will enable speed gains. Versatility of droplets enables fabrication of electronics, mechanical structures (Trusses, Cellular Lattices, meta-materials), biological materials (tissues, DNA), to name a few.

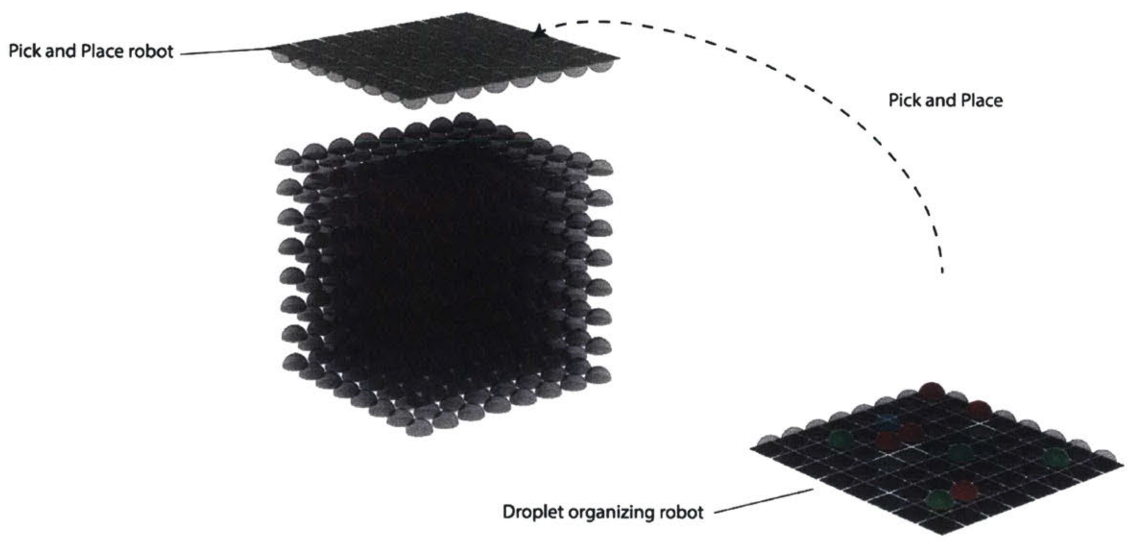

Figure 10-5: Parallel deposition of pico-liter droplets

Extending this approach with multiple electrowetting based droplet assemblers will improve the assembly speeds even further. As in Fig. 10-5, the Droplet Organizing Robot transports material from raw feed stock and organizes them as layers, while the Pick and Place Robot harvests the planar assembled unit and performs layer-wise deposition.

Chapter 11

Conclusion

In this thesis I propose the use of droplets as a form of *programmable material* for information manipulation and human interaction. Water is the medium that carries chemical and biological information. It is fundamental for survival and evolution of life. From walking in the rain to working in laboratory - water is ever present and thus important from human-interaction standpoint. Although water is generally considered to be a continuous medium, by discretizing it into smaller entities (droplets) it becomes possible to computationally control them. For this thesis I used electrowetting to bridge the computational and the physical.

Electrowetting has existed since the 19th century, however, in this thesis I have shown novel primitives for fluid manipulation and techniques for controlling large number of droplets simultaneously to further imagine the potential of electrowetting. By regulating interfacial forces through electrowetting on my platform *DropletIO*, I demonstrate the primitives: moving, merging, splitting, mixing and spreading droplets on an open surface. In developing these primitives we can begin to think of droplets as discrete units of information that can be altered computationally.

To be able to interact with droplets in our environment, I integrated DropletIO devices into many everyday objects with planar and curved surfaces. A goal for the thesis was to create *Fluid Interfaces*; droplets are one form of fluid. This is the first step towards the larger vision of being able to computationally control ambient physical materials in HCI.

In constructed large electrowetting arrays, I showed how scaling electrowetting to large areas and dense arrays with discrete components suffers from the *tyranny of numbers* problem. The *tyranny of numbers* in electronics was solved with the invention of Integrated Circuits. Similarly, by borrowing principles in the display and data storage industry electrowetting can be scaled economically.

Electrowetting is an integrated method for scaling microfluidics to complex operations. Complex microfluidic operation on a single device enables many applications beyond its use as just a research tool. Automated fluid handling such as assay preparation, cell cultures, next-generation sequencing and DNA synthesis can be done inexpensively on a desktop. This allows for the construction of miniaturized *wet lab in a box* enabling personalized biology.

I hope this work inspires artists, designers and scientists to re-imagine how one thinks about physical materials around us, and to bring computational control to establish new paradigms in programmable materials.

List of Figures

List of Tables

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