Liquido: Embedding Liquids into 3D Printed Objects to Sense Tilting and Motion

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Abstract
Tilting and motion are widely used as interaction modalities in smart objects such as wearables and smart phones (e.g., to detect posture or shaking). They are often sensed with accelerometers. In this paper, we propose to embed liquids into 3D printed objects while printing to sense various tilting and motion interactions via capacitive sensing. This method reduces the assembly effort after printing and is a low-cost and easy-to-apply way of extending the input capabilities of 3D printed objects. We contribute two liquid sensing patterns and a practical printing process using a standard dual-extrusion 3D printer and commercially available materials. We validate the method by a series of evaluations and provide a set of interactive example applications.

Author Keywords
3D printing; digital fabrication; rapid prototyping; printed electronics; capacitive sensing; input sensing; tilting; motion; interaction devices.

ACM Classification Keywords
H.5.2 [Information interfaces and presentation]: User Interfaces - Input devices and strategies.

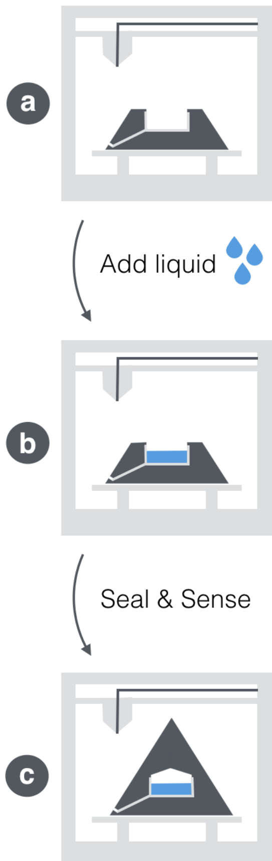

Figure 1: Fabrication process: (a) Start 3D printing, (b) stop & add liquid, (c) continue printing to seal object & sense tilting or motion.

Introduction

Tilting and motion are increasingly common interaction modalities used in smart objects such as wearables, smart phones, appliances, or toys (e.g., to control a game by tilting an object). These modalities are often used to detect posture or movement gestures (e.g., shaking). Traditionally, both tilting and motion are sensed with accelerometers.

There is an increasing stream of research towards digitally fabricating smart objects (e.g., through 3D printing) that feature interactive capabilities [9, 19, 22, 23]. Rather than post assembling components [7, 17], digital fabrication brings about the desire to provide input and output capabilities with minimal effort after the printing process. Currently, tilting and motion sensors need to be embedded into 3D printed objects after printing which is considerable (opening the object, mounting a sensor, routing multiple wires, etc.).

In this paper, we propose to embed liquids into 3D printed objects while printing (see Figure 1) to easily sense a variety of tilting and motion interactions, thereby reducing the assembly effort after printing. By 3D printing conductive parts into the objects, we can measure liquid levels and infer tilting or motion via capacitive sensing. It is an easy-to-apply, inexpensive way of extending the input capabilities of 3D printed objects with low effort. In this work, we focus on coarse-grained tilting and motion interactions which are adequate in many application scenarios (e.g., rapid prototyping or tangible games). In summary, we contribute:

- Liquid sensing patterns to capacitively measure tilt and motion via liquids in various volumetric 3D objects
- A printing process using a standard dual-extrusion 3D printer and commercially available materials
- Exemplary interactive applications
- Technical evaluations on (i) the suitability of different liquids and (ii) the accuracy of the liquid sensing patterns

Related Work

Using Liquids for Interaction

Liquids have been used in HCI for input and output before. They are often used for tactile or haptic feedback by varying the amount of liquid in an object [3], splashing onto users fingers [14], or through controlling the viscosity [10]. Moreover, researchers investigate interactions in a liquid [16], sensing touch through liquid displacement [6], and detection of liquid levels without wires [4].
The use of liquids to sense tilting is based on a known principle called *liquid capacitive inclinometers*, i.e. the tilt is derived from varying coverages of liquid on one or multiple capacitive sensors. Whereas Takemura et al. propose a liquid rate gyroscope that uses a dielectric liquid to sense tilt [21], they require a high voltage power supply and a specialized liquid. We propose to use tap water combined with off-the-shelf 3D printing and tinkering equipment (e.g., an Arduino). Moreover, many methods require electronic components that need to be produced and assembled. Our method is applicable in different (possibly moveable) parts inside of many volumetric objects out-of-the-box with little effort.

3D Printing of Interactive Objects

A stream of research investigates how to integrate interactive capabilities into 3D objects through digital fabrication. This includes redirecting in- or output channels through light pipes [2, 23], unfilled pipes [18, 11] or elastic pipes [22] in 3D printed objects. Also, research proposes techniques that integrate conductive parts directly into 3D printed objects by means of conductive wires [5], silicone [13], sprays [9, 15], inks [1], or threads [8]. However, objects fabricated with these approaches often require specialized printers and additional assembly steps. In contrast, we contribute a lightweight, easy-to-apply method that operates on standard off-the-shelf 3D printers and does not require embedding components after printing.

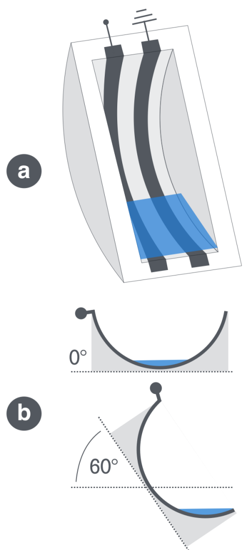

Figure 2: (a) 3D and (b) 2D view of halfpipe pattern filled with liquid.

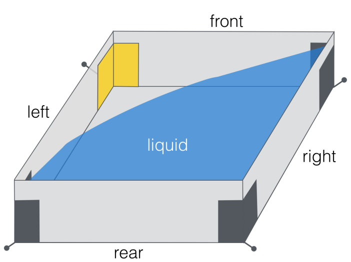

Figure 3: Tilted cubic pattern. One of the four electrodes is triggered due to lack of liquid.

Liquid Sensing Patterns

Since liquids tend to level out horizontally, they can be used to determine motion or tilting with respect to gravity. In order to leverage this effect inside of 3D printed objects, we investigate different sensing patterns that can be easily 3D printed without printer modifications and provide enough room for the liquid to flow. In this section, we present two promising liquid sensing patterns, based on modifications of the principle of liquid capacitive inclinometers, that support various tilting and motion interactions.

Halfpipe Pattern

For use cases where a continuous one-dimensional tilt in combination with minimal wiring is required, we propose the 3D printable *halfpipe pattern* (see Figure 2). It is formed like a halved cylinder to achieve the same liquid level at any tilt. Two equally sized (curved) conductive electrodes are printed parallel to each other alongside the cylindrical surface. Both electrodes are equally covered by a small amount of liquid. To measure tilting with the first electrode, we utilize the following phenomenon: The closer a dielectric liquid gets towards a capacitive sensor, the higher the capacitance. I.e., if an electrode is covered by liquid at its end, less capacitance is measured at its start (see Figure 2b). For this, the dielectric liquid has to be connected to the same ground as the sensor. Thus, we use the second electrode for grounding. In general, this pattern requires two distinct wires of which one is connected to a capacitive sensor and the other to ground. To further reduce the amount of wires, the human body can also be used as ground (for this, a user has to touch the second electrode).
To compute the tilt, we use a linear regression to map raw capacitance to tilt in degree. For calibration of the linear function, raw data for one extreme tilt and the horizontal tilt needs to be recorded. Figure 2 shows an exemplary version that is constructed to keep liquid up to ±60° and thus allows to measure continuous tilts from -60° to +60°. In general, due to the cylindrical design, this pattern is able to cover a broader range of tilts by extending the electrodes.

Cubic Pattern

While the halfpipe pattern allows measuring continuous tilts in one dimension, we further propose a cubic pattern to measure discrete tilts in two dimensions. It consists of a rectangular container with four distinct electrodes in each vertex (see Figure 3). In balanced position, all four electrodes ground each other due to the dielectric liquid. When tilting or moving an object, one or more electrodes are not grounded by others anymore. This effect can be used to infer motion or tilt (e.g., towards left) and intermediate states (e.g., towards front left). Also, horizontal balance (i.e., all electrodes ground each other) and flipping the object over (i.e. no electrode is grounded) can be detected by the number of electrodes that ground each other (see Table 1). For this pattern, no calibration is required.

Prototypical Implementation

3D Printing Process

In essence, fabrication follows the standard 3D printing process: After designing or downloading a 3D model, one of the sensing patterns is inserted into the model with a standard CAD tool. Currently, the wires that connect a pattern to the outside need to be designed manually. However, this can be easily automated by using routing algorithms (c.f. [18, 19]). Then, the 3D model is printed on a standard dual-extrusion 3D printer (see Figure 4). During printing, the printer needs to be stopped once to fill in the liquid (see Figure 1). This step can be automated by a liquid pump mechanism attached to the printer (c.f., [12]). Also, depending on the size of the pattern, the amount of liquid varies. We found through empirical tests that the smallest amount of liquid that adequately covers all electrodes is best for op-

# of electrodes grounding each other	tilt
four	balanced
three	to one vertex (4x)
two	to one edge (4x)
zero	flipped over

Table 1: Possible tilt states when using the cubic pattern.

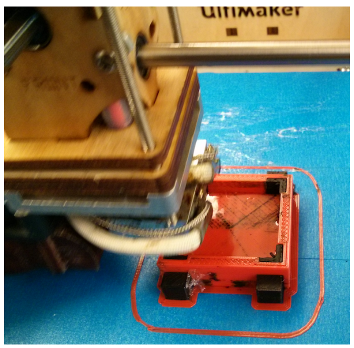

Figure 4: 3D printing of cubic pattern with liquid already filled in.

eration. After this intermediate step, the remaining printing process is again fully automatic.

Apparatus

We utilize an Ultimaker Original 3D printer with Dual Extrusion Kit (ca. $1500), ordinary PLA (ca. $30 per kg), and a commercially available conductive PLA by Proto-pasta (ca. $96 per kg), which has an average resistivity of 30 - 115 Ω * cm. We identified an optimal extrusion temperature of 220℃ (nozzle diameter 0.8 mm) with the cooling fan turned on. Our controller board consists of an Arduino Mega 2560 (tethered to a PC) and a MPR121 capacitive sensor (12 sensing pins at a sample rate of 29 Hz). Raw capacitance data is reported as ADC count ($C = const./ADC$) [20]. We connected the sensing pins and the printed objects with crocodile clips or bread board jumper cables.

After testing different easily available liquids (see evaluation section), we opted for tap water as we found that the correlation between tilt and capacitive raw data is the most linear and thus allows covering the full range of tilts at nearly the same resolution. Moreover, it is easily available and can be used without safety precautions.

Tilt and Motion Interactions

Using the previously described sensing patterns, a variety of motion and tilt interactions are detectable (see Figure 5).

Tilt Interactions. The most basic interaction is *tilting* in various directions. Using the cubic pattern, tilts towards *left*, *right*, *front*, and *rear* and intermediate states (e.g., front left) can be detected. Moreover, *flipping* an object over upside down to simply trigger an action can be very lightweight (e.g., like turning a dice). Balanced and flipped states are distinguishable with the cubic pattern.
Based on the halfpipe pattern, *rotating* interactions can be

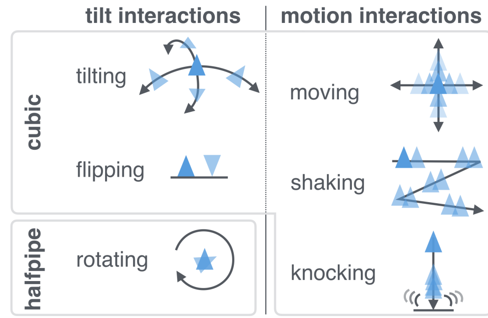

Figure 5: Illustration of various tilt and motion interactions supported by the cubic or halfpipe pattern.

supported that require more precise input than discrete tilts. For instance, the pattern can be directly embedded into rotation-aware 3D printed objects. In complex objects, this can also be used to implement 3D printed tangible controls (e.g. a tactile rotaty knob containing a halfpipe pattern).

Motion Interactions. By quickly *moving* an object, liquid is pushed into different regions of an object. This can be used to sense the direction of motion with the cubic pattern. Based on this, *shaking* in different directions (e.g., left to right or front to rear) can be distinguished by analyzing movements over time. Moreover, repeatedly *knocking* an object (with a cubic pattern) onto a rigid surface can be detected by analyzing balanced and flipped states over time.

Example Applications

We implemented three example applications based on either the halfpipe or cubic sensing pattern.

Tangible Airplane Game (cubic)

We printed an airplane model with an embedded cubic pattern (2x2 cm) connected to a capacitive sensor via four

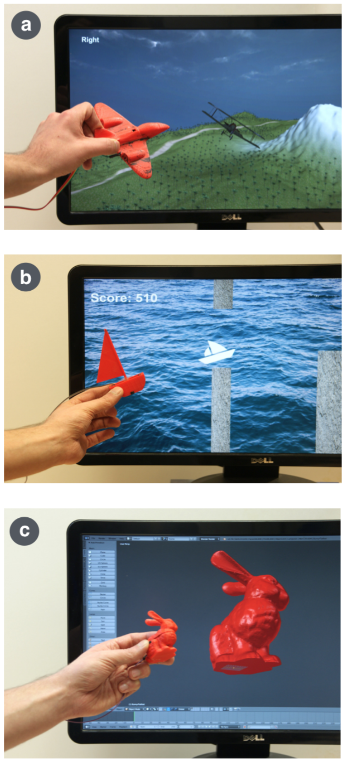

Figure 6: Interactive example applications: (a) flying an airplane simulation, (b) avoiding obstacles with a physical ship, and (c) rotating a physical object for 3D navigation.

distinct wires (see Figure 6a). In combination with a flight simulator, the physical object can be used to fly through a territory by tilting the plane to varying directions (e.g., tilt to front to dive). Shaking the airplane restarts the simulation.

Tangible Ship Game (halfpipe)
We printed a simple sailing ship featuring an embedded halfpipe pattern (see Figure 6b). By tilting the ship up or down, a user controls the direction in which the ship is constantly swimming, thereby guiding the virtual ship safely past varying obstacles.

Tangible 3D Navigation (halfpipe)
For CAD experts, rotating a 3D view of a digital model is easy. However, for novice users our method can be used to easily explore digital 3D models of objects by rotating their 3D printed counterparts. To illustrate this scenario, we printed the well-known Stanford Bunny (54x54x45 mm) with a halfpipe pattern inside (see Figure 6c). This can be used to inspect different views of a 3D model around one axis (in case of the Bunny the lateral axis) by manipulation its physical proxy object. By including more halfpipe patterns, further axes can be controlled.

Evaluation

Comparison of Different Liquids
To investigate which liquids are most suited to be embedded into 3D printed objects while printing and to sense one-dimensional tilt via the halfpipe pattern, we tested four liquids based on water: salt solution (0.05g/ml), vinegar solution (0.1g/ml), dish soap solution (0.001g/ml), and pure tap water. We focused on easily available and cheap liquids.

Setup and Measurements. Data was recorded on a PC connected to an Arduino Mega 2560. Capacitive data was measured by a MPR121 chip (sample rate 29 Hz) which was connected to one electrode (3.5 mm thick) of a halfpipe pattern (40x15x18 mm LxWxH). The second electrode was connected to the Arduino's ground. As ground-truth reference a MPU 6050 tilt sensor was used. The tilt sensor and the halfpipe pattern were both mounted on a rod to enforce equal tilt.
For each test cycle 1 ml of liquid is dispensed into the halfpipe pattern. The rod is turned several times to either side (range from -60° to 60°). After a test cycle, the liquid is removed, and the pattern is cleaned and dried.

Results and Discussion. We tested each liquid according the procedure described above. We found that tap water has the broadest range of data (172 counts) and vinegar the least range (50 counts). Salt (124 counts) and dish soap (117 counts) have nearly the same range.

Figure 7 illustrates the polynomial trend lines (2nd degree) of all liquids for varying tilts. The trend line for tap water shows that mean values arranging around an almost linear

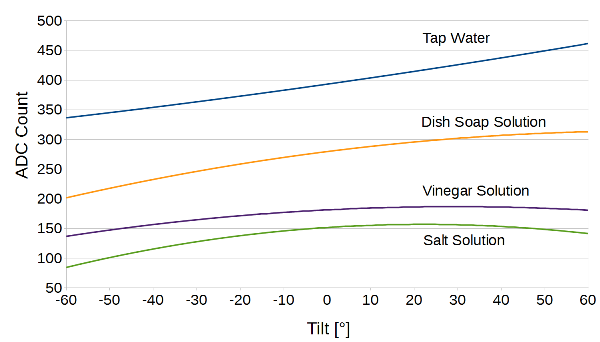

Figure 7: Trend lines for tap water, dish soap solution, vinegar solution, and salt solution showing the dependency between ground-truth tilt and measured counts for the halfpipe pattern.

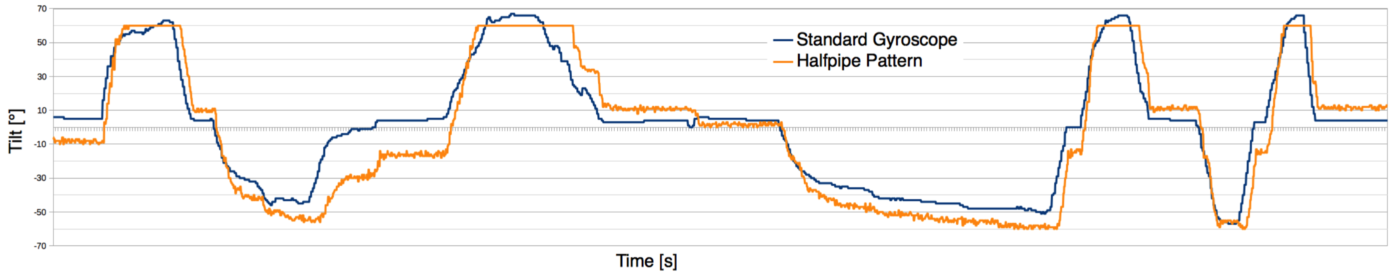

Figure 8: Comparison between tilts reported by the halfpipe pattern (orange) versus a MPU 6050 tilt sensor (blue) over a timeframe of 184s.

trend line ($f(x) = .0016x^2 + 1.0411x + 393.26$). In contrast, the trend lines for salt, vinegar, and dish soap solution level off for larger tilts. Especially for salt and vinegar, values drop towards 60°. As we require an invertible function to unambiguously compute tilt from raw data, these liquids are less suited. Also, the range of vinegar is very low. Thus, a precise interpretation of vinegar values is more difficult. We finally selected tap water for our measurements, because of its invertible and linear trend line. Despite its invertible trend line, dish soap solution leaks through the container (probably due to reduced surface tension).

Accuracy of Tilting

We compared ground-truth tilts with the halfpipe pattern (containing 1 ml tap water). As illustrated in Figure 8, there is an offset that is often towards the last extreme (±60°). I.e. if the tilt is extreme, the halfpipe pattern tends towards that particular side. One reason may be that liquid remains on some electrode parts and connects them unintentionally.

Limitations

First, our method requires an insulating container and thus cannot be used for metal prints etc. Second, some 3D printers move their build plate while printing, which may result in spillage of liquid. Third, we evaluated our prototype at room temperatures. As temperature influences the volume of a liquid, its usage at other temperatures may either require another amount of liquid or a recalibration.

Conclusion and Future Work

In this paper, we contribute a method to capacitively sense a variety of tilting and motion interactions by embedding liquids into 3D printed objects which is applicable with standard dual-extrusion 3D printers and commercially available materials. We propose the halfpipe and cubic printing patterns that can sense continuous one-dimensional or discrete two-dimensional tilts or motions. Also, more complex motions such as flipping, shaking, and knocking objects are supported. To validate our method, we compare different dielectric liquids and evaluate the accuracy. By providing exemplary applications we show the applicability of our method. For future work, we want to investigate multiple sensing patterns in one object and other ways of exploiting liquids for interaction with 3D printed objects.

Acknowledgments

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