Social Sensing with a Smart Cup

Rethinking ubiquitous smart sensing of social behaviour in the wild

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Abstract

This paper presents a smart drinking cup prototype platform for social sensing studies. Recording the dynamics of unscripted human interactions in social settings can be challenging and often requires the participants to wear external hardware. This leads to greater participant discomfort and behavioural changes. To address this, we propose a prototype for a smart sensing cup: a multi-sensor data collection device integrated into a drinking cup. A hydrostatic pressure sensor is used for the volume and temperature measurements of the contents of the cup. Orientation data is gathered with a three-axis accelerometer, measuring the pitch of the cup. Detection of whether the cup is being held by a participant is ensured using a capacitance sensor. The sampling rate for all sensors is 10 Hz and can store up to an hour of data on the device. Using the sensor data we are able to detect whether a cup is being held, identify drinking events and fluid intake and give live feedback on this using an LED.

1 Introduction

Studying human interactions in social settings is crucial for developing socially intelligent systems. However, these studies, such as ConfLab [8] often rely on external or wearable sensors for data collection. An alternative approach is to embed the sensors into the already prevalent accessories during these social activities. We believe that the detection accuracy will improve with signals measured at the source of the activity. For example, instead of trying to identify drinking from audio, video or accelerations, measured externally or by using body-worn sensors, we can measure this directly with sensors integrated into the cup.

From this follows the main research question: *how can we best design a cup suitable for social sensing studies?* We answer this by looking at existing studies involving wearable sensors and smart cups and seeing how can integrate these into a prototype. Then we perform a few tests, simulating behaviour in a social setting.

Specifically, we look at *what liquid sensing technique is most suitable for social sensing studies* and *how can these sensors be integrated into a drinking cup?*

The contribution of this study is:

- The first integrated multi-sensor drinking cup for social studies including pressure, temperature, accelerometer and capacitance sensors.
- Design and evaluation of the Smart Cup prototype.

2 Related Work

Two domains converge in this work, the domain of wearable sensing commonly used in social sensing studies and liquid level sensing, previously investigated for measuring fluid intake for the elderly and limiting alcohol consumption.

2.1 Wearable sensing

With wearable sensing, a data collection device is attached to the participants. Various studies have been done in this field but for this paper, the ConfLab [8] study was used as a basis. In this study, a multi-model multi-sensor data collection approach was taken to record in-the-wild free-standing social conversations. Data was captured from both overhead cameras and custom wearable sensors, with the wearable sensor being the most relevant for this study. For the Conflab study, the Midge sensor was used, attached to a badge, recording body motion, audio and Bluetooth-based proximity. In the MatchNMingle study, a similar approach was taken but recording just accelerometer and radio proximity data from the wearable device [2].

2.2 Liquid level sensing

Several smart cup platforms exist though they mostly focus on fluid intake, either to prevent dehydration [7] or overconsumption of alcohol [1].

Even though these cups serve a different purpose they essentially do the same, which is measuring the amount of liquid in the cup. Kreutzer et al. summarises the various measuring techniques into the following categories [6]. While there are theoretically more possible implementations for measuring the liquid level, these are the ones that have been implemented in previous studies [5].

A method for conductive fluid detection is described in [6]. Here a flexible sensor board consisting of detection electrodes is inserted along the side of the board with a reference electrode at the bottom. The electrodes are gold-plated to prevent chemical reactions with the fluid. If immersed in a fluid, there is only an electric connection between the reference and the detection electrodes, which allows us to measure the filling level. The drawback of this method which certain types of liquid like milk or sugar, stick to the side of the cup sometimes distorting the measurements.

The liquid level in a cup increases the hydrostatic pressure at the bottom with sensor pressure:

$$p = p_{\text{atmospheric}} + p_{\text{hydrostatic}} \tag{1}$$

Since the density of liquids is relatively similar we can use the difference in this pressure to estimate the amount of liquid in the cup with:

$$p_{\text{hydrostatic}} = \rho_{\text{liquid}} \cdot g \cdot h \tag{2}$$

To calculate the hydrostatic pressure we have to know the atmospheric pressure which can fluctuate based on weather conditions. In a previous study, this was done by having a second sensor exposed to the environment [4].

With hydrostatic pressure, we measure the mass of a small area, but another possibility is weighing the entire cup instead by putting it on a scale. By integrating this scale we are able to take measurements without a sensor exposed to the liquid, however, we can only take measurements when the cup is on a fixed surface [4].

Another approach is measuring the capacity of the contents of the cup and comparing this to a reference value [3]. A prototype has been made with CLC Series from First Sensor

AG placed on the side of a mug, shielded with aluminium foil to prevent influence from outside sources [4].

3 Methodology

We answer the research question by building various prototypes after establishing the requirements it should satisfy.

3.1 Requirements

In order to accurately capture the dynamics of human interactions in social settings, we have come up with the following requirements that the smart cup should satisfy.

The sampling rate for all collected data should be at least **10 Hz**. This sampling rate was chosen as a compromise between not having enough space to store the data and the data not being useful because the fidelity is too low, for example with detecting motion.

We want to capture the social interactions as naturally as possible, with little to no interruptions. Therefore we have chosen a long recording duration of at least **60 minutes**.

From discussions with the client we have identified the following list of requirements:

- Should look like a regular cup by integrating the sensors
- Should sense the orientation of the cup
- Should sense the temperature of the liquid in the cup
- Should sense the amount of liquid in the cup with an accuracy of 10 ml
- Should sense whether a person is holding the cup

As seen in Section 2 there might be a bit of overlap between these requirements, i.e. given that we know the orientation of the cup at certain time frames we might be able to detect whether a person is holding the cup. The focus of this study, however, lies in collecting this data directly from the sensors, to ensure validity and to provide a basis for training machine learning models in future research.

3.2 Sensors

We have considered all of the options from the related work section and concluded that the hydrostatic pressure detection approach is the most suitable for this application. This is for the following reasons. First of all, it allows us to continuously take measurements, which is not possible with the force detection method. It can be integrated into the bottom of the cup, hiding the sensors from the participants resulting in more natural behaviour. This would not be possible with the capacitive sensor since the probes would have to be on the outside with proper insulation. Lastly, the conductive method was omitted because integrating the probes in a waterproof way inside the cup would not be feasible, with the pressure sensor we just have to expose the sensor with a tiny hole. With this, we also get temperature information because these are packaged inside the same sensor.

The orientation of the cup will be measured with an accelerometer. The accelerometer measures the acceleration of the cup which is, when the cup is relatively stationary, mostly gravity pointing downwards. If the sensor measures something else, we know that the cup is tilted. We can get the orientation by comparing the sensor reading $\vec{a} = [x, y, z]^{\mathrm{T}}$ with the reference $\vec{b} = [0, 0, -1]^{\mathrm{T}}$. For this, we use the following formula

$$\vec{a} \cdot \vec{b} = |\vec{a}| \cdot |\vec{b}| \, cos(\theta) \tag{3}$$

and assuming the cup is stationary and thus normalising $\vec{a}$ and $\vec{b}$ this results in

$$\theta = cos^{-1}(a_z) \tag{4}$$

where a_z is the normalised z value of the sensor and θ the pitch of the cup.

To measure whether the cup is being held, we use a capacitive sensor. We do this by wrapping the cup in conductive material which we then connect to the sensor. This allows us to detect things near the cup with a different dielectric constant than air, such as hands [9]. This is quite similar to the method used for liquid detection, only on the outside instead of the inside. Since the inside is not insulated, the liquid might also influence these readings.

The specific sensors used are listed in Table 1.

Sensor	Chip
Accelerometer	LIS2DW12
Pressure	ILPS28QSW
Temperature	ILPS28QSW
Capacative	AT42QT1070

Table 1: Sensors on board

3.3 Hardware

With integrating the sensors mentioned above into a cup, appearance was a big consideration, as stated in the first requirement. For the pressure sensor is also important that it is placed at the lowest part of the cup, to measure whether or not the cup is (almost) empty. For these reasons, we opted to place the sensors under the cup with a custom two layered board. On the cup side of the board, it features a waterproof pressure sensor, exposed to the liquid with a small $3\,\mathrm{mm}$ whole as shown in Figure 1, made watertight with food safe epoxy. The other side features the rest of the sensors as well as small RGB LED to give real-time feedback on the state of the cup. The cup is wrapped in aluminium foil connected to the capacitive sensor to function as a capacitive surface.

For the microcontroller the Raspberry Pi Pico RP2040[1] is used, chosen because it is widely available and has $2\,\mathrm{MB}$ of onboard flash memory allowing us to store the recorded data without an external storage device. It communicates with the sensors over I^{2}C. The brightness of the RGB LED is controlled using three PWM channels.

To keep the appearance of a regular cup we slide another cup over the sensor cup, with the sensor board sitting in the bottom compartment formed by the two stacked cups as shown in Figure 2. This leaves a compartment with a height of $20\,\mathrm{mm}$ leaving room for the the Pico and battery as well.

[1] https://www.raspberrypi.com/documentation/microcontrollers/raspberry-pi-pico.html

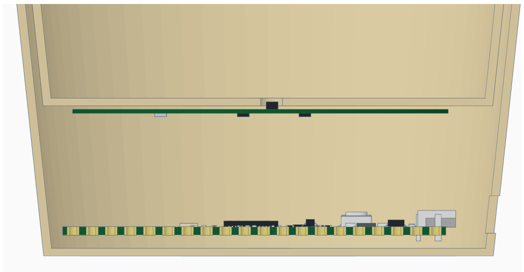

Figure 1: Layout showing the assembly of the smart cup. Attached to the inner cup is the developed Smart Cup board, and the bottom is the Raspberry Pi Pico microcontroller

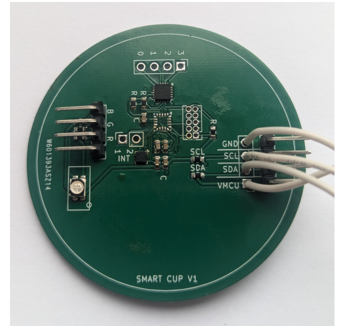

Figure 3: Smart Cup Board

(a) Inner cup wrapped with aluminium foil for capacitive touch sensing

(b) Fully assembled cup

Figure 2: Pictures of the Smart Cup prototype

The USB port is exposed by a hole in the outer cup, used to charge the cup and download the recorded data.

3.4 Software

As mentioned, the Raspberry Pi Pico is used as the microcontroller for this prototype. This board can be programmed using either the C/C++ SDK or the MicroPython[2] SDK. With the C/C++ option, the code is compiled directly for the MCU which is more memory and power efficient and runs faster. MicroPython is a more efficient implementation of the Python 3 programming language optimised for embedded systems. MicroPython's interpreted nature introduces some overhead, however, it makes up for this by ensuring that the code is easy to understand, making it more suitable for this prototype.

Every $100\,\mathrm{ms}$ we poll the sensors over I^2C. We then interpret the data received from the sensors and write them into a CSV file. The touch and temperature values are stored directly but for liquid level and pitch, we have to do additional processing.

To get the hydrostatic pressure from the sensor we have to subtract the atmospheric pressure, see Equation 1. The atmospheric pressure can fluctuate based on weather conditions. When the device boots up we assume it is empty and thus collect the atmospheric pressure. We can then use Equation 1 and 2 to calculate the height of the liquid inside the cup. The cup is a truncated cone, known as a circular cone frustum. Its volume can be calculated with:

$$V = \frac{\pi h}{3}(r_1^2 + r_1 r_2 + r_2^2) \tag{5}$$

where r_1 and r_2 are the base and top radii and h is the height of the frustum [10]. After measuring the base and top radii plus the total height we calculate the total volume of the cup. To get the liquid volume at an arbitrary height, we need to know the radius r_2 at that specific height. Since the slope of the cone is a straight line we can calculate this with:

$$r_2 = r_{\text{base}} + \frac{r_{\text{top}} - r_{\text{base}}}{H} \cdot h \tag{6}$$

where r_{base} and r_{top} are the base and top radii of the cup, H is the total height of the cup and h is the liquid height. Using Equation 5 with $r_1 = r_{\text{base}}$ and liquid height h we are then able to calculate the volume of the liquid inside the cup.

The pitch of the cup is recovered using Equation 4.

4 Experimental setup

To verify that the measurements from the prototype are correct we conduct two experiments. First, we record data from interactions with the cup in a social setting. This allows us to get a general idea of the quality of the recorded data. However, we do not know the exact volume of the sips and thus cannot measure the accuracy of the liquid-level sensing. To verify this we conduct a second test, consisting of filling and emptying the cup with known quantities.

To compare the measurements against ground truth, we have added a script consisting of instructions like "Pick up" or "Take sip". These instructions are sent over serial and included in the measurements CSV. This CSV also includes a timestamp in microseconds since the board was powered on and of course the measurements for the sensors. For the first experiment, we used the script depicted in Table 2. At "Fill cup", the cup is filled with $25\,\mathrm{mL}$ of water, at "Pick up" we pick up the cup from the table, at "Take sip" we raise the cup to the mouth and take a sip, at "Wait" we just hold the cup and at "Put down" we put the cup down on the table. We

[2] https://micropython.org/

Instruction	Duration (s)
Get ready	10
Fill cup	10
Pick up	5
Take sip	5
Wait	5
Take sip	5
Wait	5
Take sip	5
Wait	5
Put down	5

Table 2: Instructions script for the first experiment

then plot these results using Matplotlib with the instructions as annotations to confirm that the sensor reading matches the expected output.

For the second experiment, we want to verify the accuracy of the liquid-level sensing. This is done by adding $250\,\mathrm{mL}$ of water to the cup and then removing $10\,\mathrm{mL}$ from the cup every $10\,\mathrm{s}$ using a syringe. Since this process will happen manually there will be some delay between the reference value and the measured value. To account for this, we will compare these values at the end of every reference interval such that we know for certain the specified amount of liquid has been removed. The mean absolute error will be derived from these measurements to get the accuracy of the sensing method.

5 Results

The measurements obtained from the first experiment are illustrated in Figure 6. The capacitance value exhibits a notable increase and then decrease during the cup-filling process. This indicates a significant influence by the liquid inside the cup, with higher readings of around 1600 with approximately $100\,\mathrm{mL}$ of water, decreasing till 1400 with $250\,\mathrm{mL}$ of water. When the cup is picked up and put down, we see a difference of 50 but the effect of the amount of liquid inside the cup is greater than touching versus not touching. Figure 4 confirms this while also showing an inverse relationship between the volume and the capacitive value unless the cup is empty.

When the cup is tilted for drinking, the pitch increases, indicative of a change in orientation. At this time the liquid volume reading momentarily decreases. This occurs because tilting the cup reduces the pressure detected by the sensor. Upon returning the cup to an upright position, the recorded volume decreases steadily after each sip.

The measurements obtained from the second experiment are illustrated in Figure 5. As expected the measured value falls a bit behind the expected value, again due to the manual filling and emptying of the cup. Note that at the end we observe that we still measure some liquid inside the cup. This is because we were unable to fully empty the cup using the syringe. Using the described method in Section 4, we arrive at a mean absolute error of $4.4\,\mathrm{mL}$.

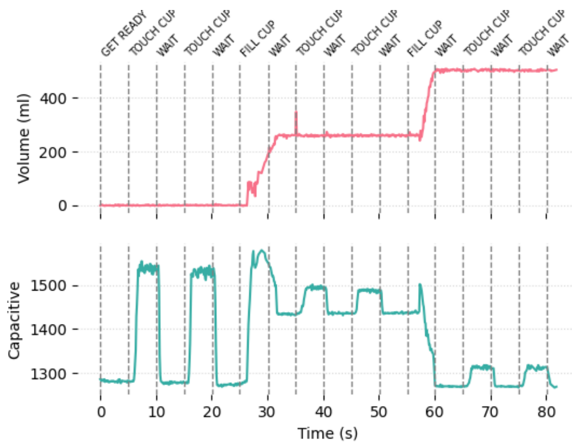

Figure 4: Capacitive measurements of touching the cup at different liquid volumes.

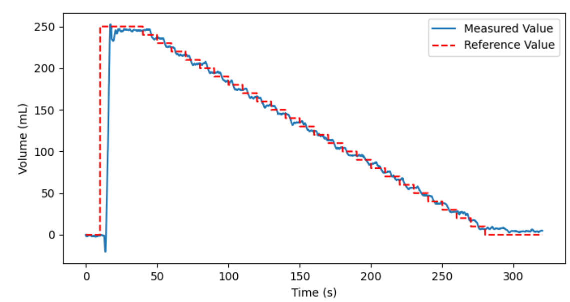

Figure 5: Volume measurements from experiment 2 compared to reference value

6 Responsible Research

In this section, we reflect on the ethical aspects of this research and discuss the reputability of the methods. Since the participants would be drinking from this cup food safety is an important concern which will be discussed first. After we go into the reproducibility of the prototype.

Only the pressure sensor and the cup itself are exposed to the liquids. The cups used for this prototype are made of polypropylene and have been approved for food use. The pressure sensor has been sealed with food-grade epoxy. To ensure hygiene the cup is thoroughly cleaned with dish soap in between experiments.

Given the nature of this study, i.e. mostly hardware instead of software, it will be harder to reproduce than most. However careful consideration has been taken to ensure that the prototype can be recreated since one of the objectives is that this design of this prototype can be used in further social sensing research. All software (MicroPython) and hardware schematics (Kicad) have been made available in a public repository[3]. The Jupyter notebook used for visualisations of the CSV files has also been added to this repository.

[3]https://github.com/ThijmenStar/smart-cup

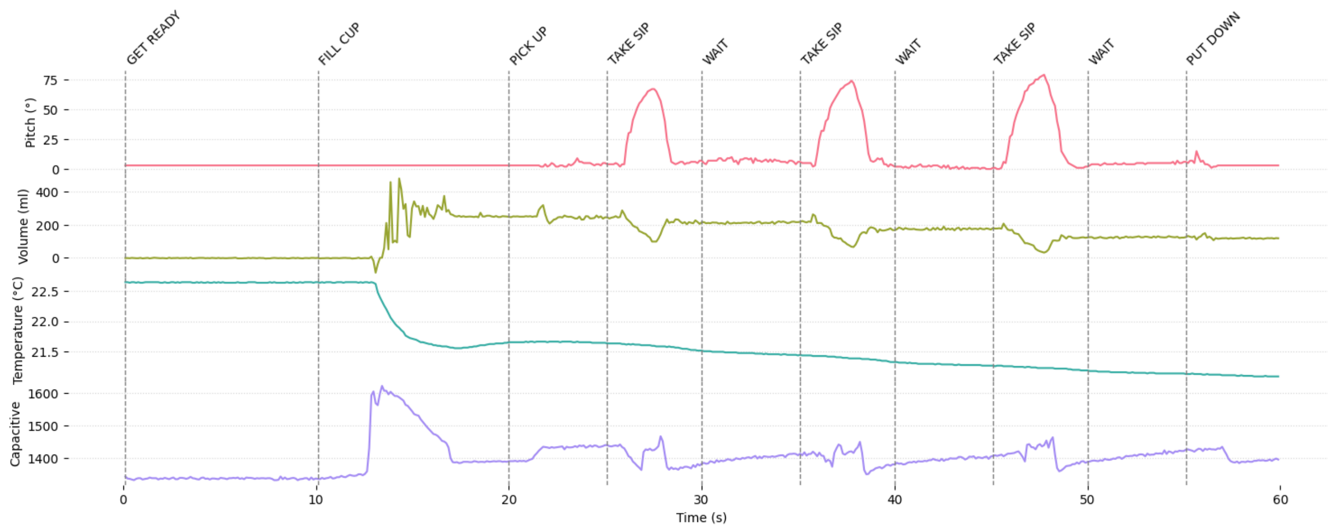

Figure 6: Sensor values from experiment 1, annotated with labels from the instructions

7 Conclusion

This contribution aims to provide future social sensing studies with a blueprint for how to build a cup with integrated sensors.

For liquid level detection, we investigate several methods and conclude that a pressure sensor is most suitable for this application, we integrate it into the cup by exposing it with a small hole and designing a two-sided PCB, containing the pressure sensor on the top, and the rest of the sensors on the bottom. This enables it to be easily sealed with epoxy to ensure waterproofing. We measure the atmospheric pressure when the device is turned on which we then subtract from the sensor reading to get the hydrostatic pressure. Using the hydrostatic pressure we calculate the amount of liquid in the cup, which we achieve with a mean absolute error of $4.4\,\mathrm{mL}$

To measure the orientation of the cup, an accelerometer is used. By measuring the direction of the gravitational acceleration this allows us to sense the pitch of the cup, which significantly increases during drinking episodes.

Capacitive sensing was used by wrapping the cup in aluminium foil connected to the sensor with the aim to detect whether the participant is holding the cup. This has proven to be unreliable as the measurements are heavily influenced by contents inside the cup.

8 Future work

Further research on this topic can be split into two categories, turning the prototype into a large scale research ready device and conducting such large scale research.

Ensuring readiness for large scale research would involve integrating the microcontroller and battery module into the sensor board itself. This would significantly speed up manufacturing since no manual soldering would be required. Using cups with an integrated enclosure instead of modifying off the shelf cups would be an improvement in this regard as well.

Even though small experiments were conducted to test the sensing ability, a proper full scale social sensing research using this prototype would be the next logical step.

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