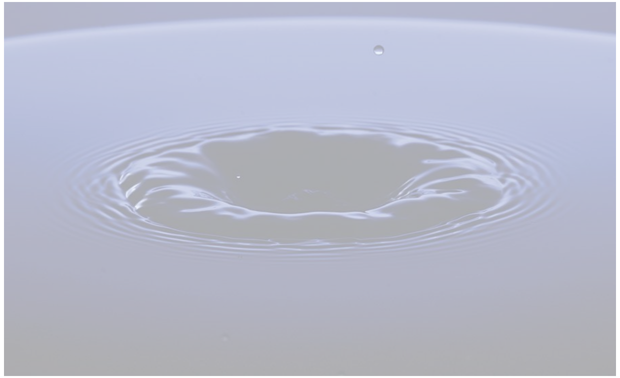
Liquid Testing with Your Smartphone

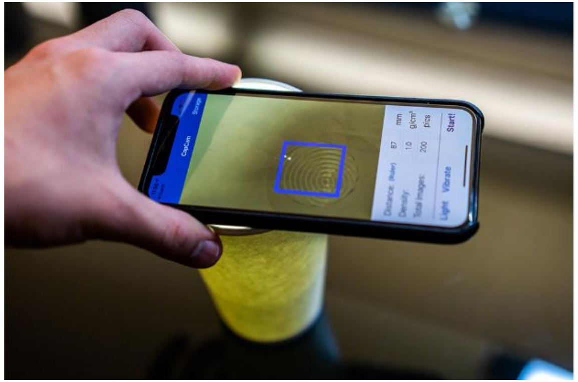
Tu Luan
Brandon Feng

Introduction

- **Surface tension** measurement can be used as a tool for
    - testing **water contamination**.
    - measuring **alcohol concentration** in drinks.
    - identifying the **presence of protein** in urine to detect the onset of kidney failure.



Introduction cont.



- Today, measurements of surface tension are done in a lab environment using **costly instruments**.
- Solution: measure surface tension using only a smartphone.
- Contribution: New algorithm that uses the small waves on the liquid surface as a series of lenses that focus light and generate a characteristic pattern. Then use the phone camera to capture this pattern and measure the surface tension.

Related Work: Liquid Testing in Mobile and Ubiquitous Computing

- Test liquid by measuring the time delay and power attenuation incurred by an RF signal as it traverses the liquid of interest. (**TagScan** and **LiquID)**
    - Requires complex setups (containers/robots)
    - Due to the properties of RF signals, the systems needed to be carefully calibrated.
    - Large errors/ avoid measuring exact values.
- Identify liquids using RF coupling/ RF reflection (**RFIQ, RadarCat** respectively)
    - Can be apply only on limited types of liquids or concentration level.
    - Cannot be generalized to unseen liquids.
- Identify liquids using optical absorption
    - Require custom hardware
    - Have a relatively limited resolution.

Related Work: Measuring Surface Tension

1. Current generally used methode: tensiometer
   a. Based on four physical properties: Force, Pendant drop, Contact angle, Capillary waves.
   b. high accuracy, expensive
2. Wei et al
   a. Use cell phone camera to capture **images of capillary waves**
   b. it ignores the **rolling shutter effect**, which leads to poor performance
   c. It requires **custom hardware**: a large container, a signal generator, anda paper screen.
3. Goy et al
   a. use cellphone cameras to capture **images of a drop of liquid**.
   b. requires **specialized equipmen**t to exercise tight control of the drop's size and shape.
   c. requires **extreme cleanliness** and a complex measurement procedures.

Method

Use vibro-motor to create <u>waves</u> at the liquid surface

Use flashlight + camera to capture the pattern that allows us to compute <u>wavelength</u>

Knowing wavelength + vibration frequency → surface tension estimates

$$\gamma = \frac{(2\pi f)^2 - g(2\pi/\lambda)}{(2\pi/\lambda)^3}\rho. \qquad (2)$$

This equation provides a procedure for measuring surface tension using capillary waves. Specifically, we can use a vibration source to generate capillary waves on the liquid's surface. Knowing the vibration frequency f, we can substitute the gravity term and the liquid density from the corresponding data sheets.[1] Hence, all we need is to measure the wavelength λ in order to measure the surface tension.

Method

$$\lambda = \frac{p}{r_{d+h} * (d+h)/d} = \frac{p}{r_d}, \tag{7}$$

where p is the number of pixels between two consecutive bright rings, and r_d is the camera resolution for objects at distance d, i.e., at the liquid surface.

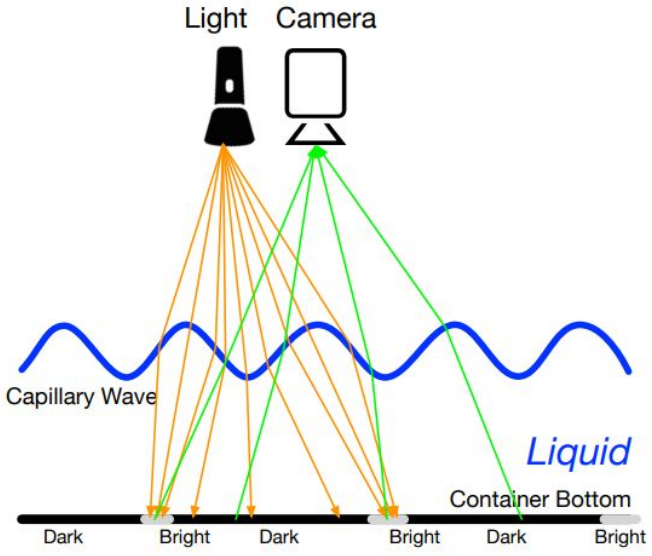


Figure 2: An cross-section illustration of the setup. Because of refraction, light rays are focused/diverged by the crests/troughs of the waves, resulting in a series of dark and bright rings on the bottom.

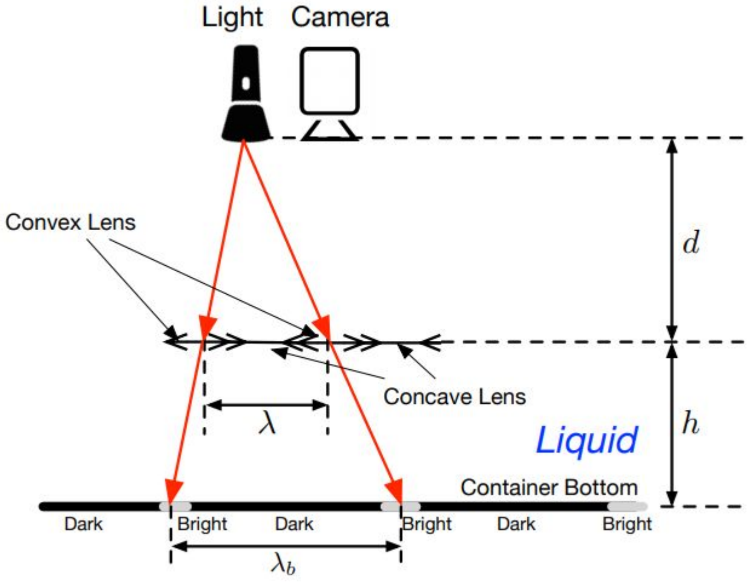
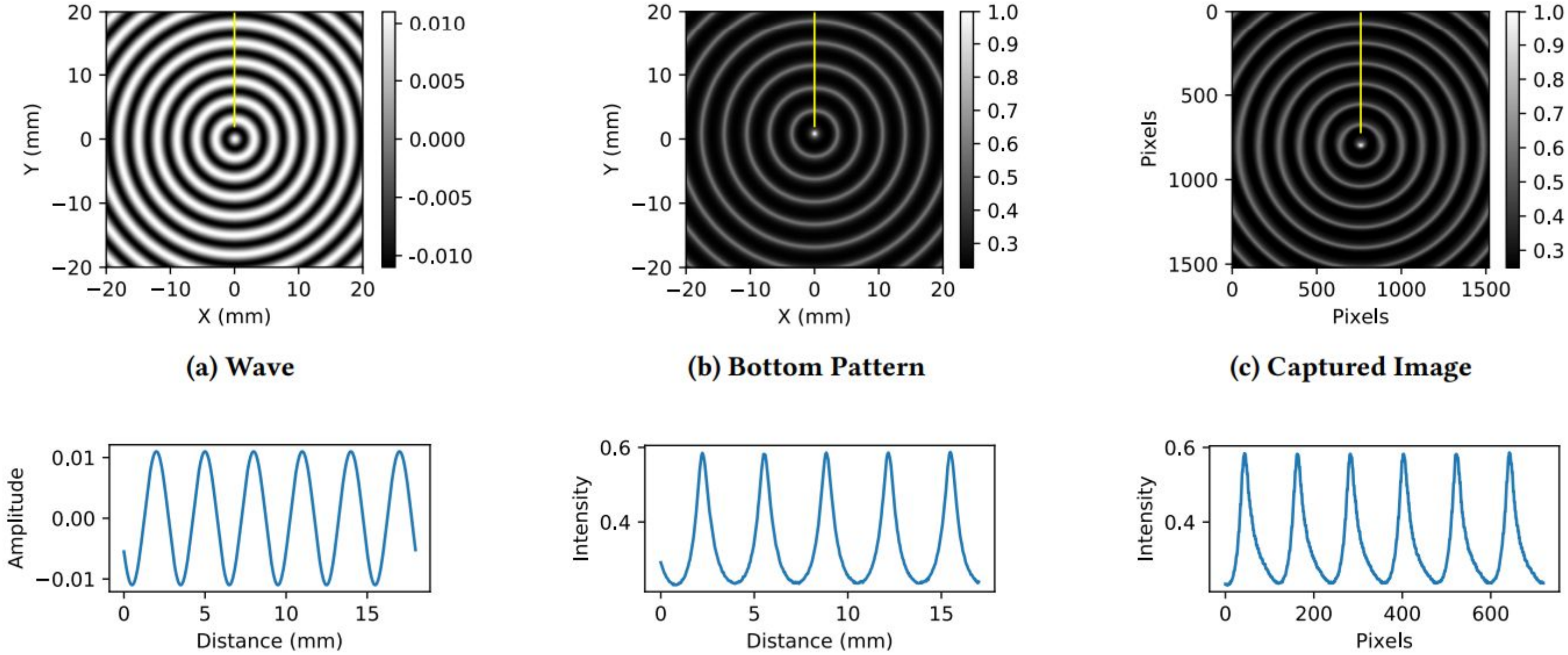


Figure 3: An illustration of the wavelength calculation. We plot only the rays that pass through the center of the crests of the waves, which do not bend.



(a) Wave

(b) Bottom Pattern

(c) Captured Image

(d) Cross section of Wave

(e) Cross section of Pattern

(f) Cross section of Image

Figure 4: A simulated experiment showing the relation between the waves on the surface, the pattern on the bottom of the container and the captured image. Figures on the second row show the pixel value along the yellow line in the corresponding first row figure. Comparing 4d with 4e, we see that the crests of the pattern on the bottom are both sharper and higher value than the crests of the waves on the surface. This is due to the focusing effect on the lenses. Also note that in 4f, the crests are shifted to the left; this is because the camera and the light are not co-located.

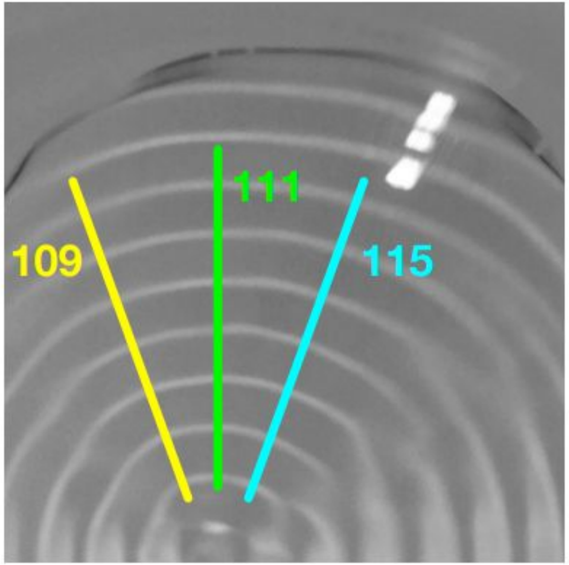
Method

Challenges

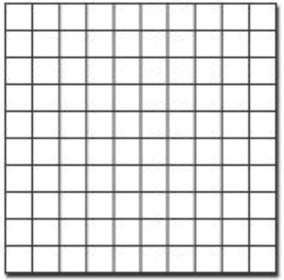
- Rolling Shutter Effect
- Unstable Vibration Frequency

Method

Rolling Shutter Effect



Rolling Shutter



Total Shutter

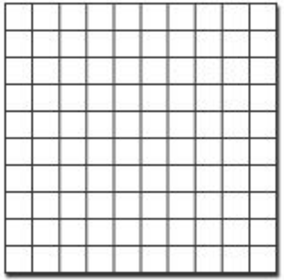


Figure 5: A sample image taken by a smartphone. The three lines represent three radii with different directions. Numbers besides the lines are the corresponding wavelength measured in number of pixels, and they are different from each other. This suggests that picking a wrong radii may result in a significant error.

Method

Correcting Rolling Shutter Effect

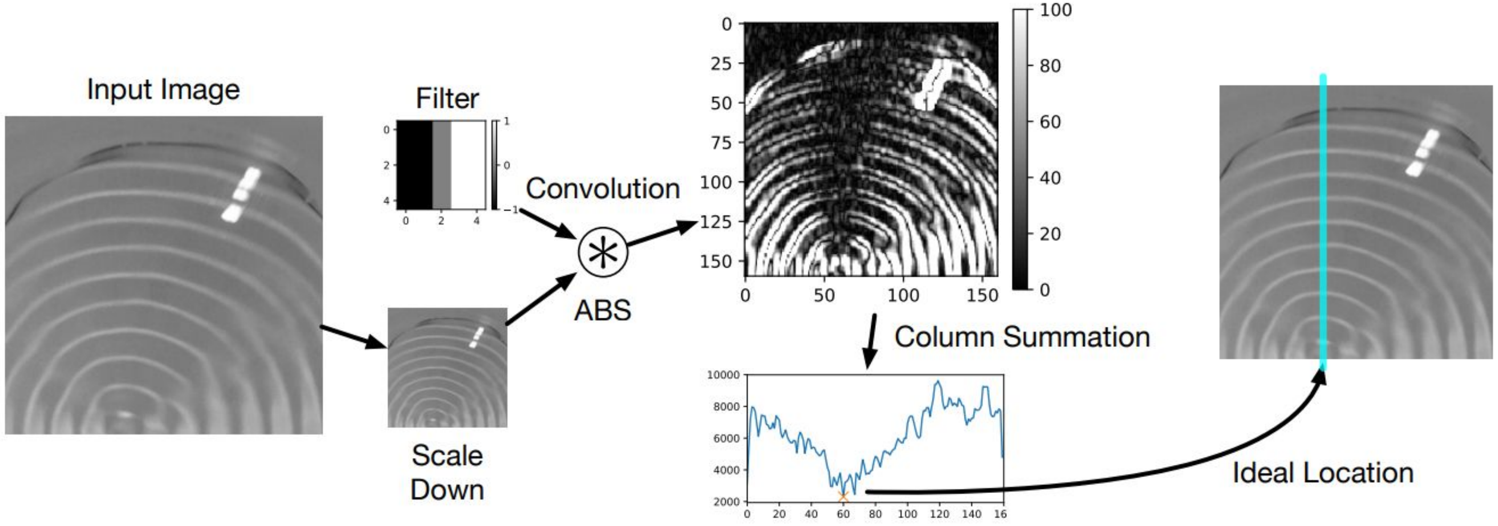


Figure 7: The algorithm for identifying the ideal location along which to measure the wavelength. We first scale down the image, and convolute it with a filter for detecting local symmetry. Then calculate the sum of the absolute values for each column. Then the column with lowest sum is the location where its wavelength is not affected by the rolling shutter effect.

Method

Unstable Vibration Frequency

Create a histogram of the all wavelength estimates

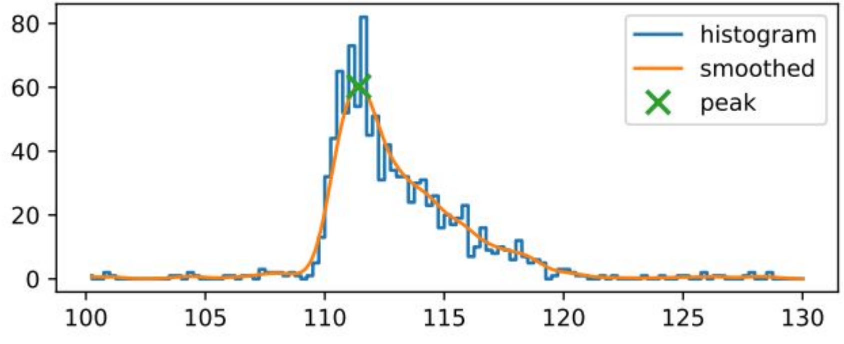
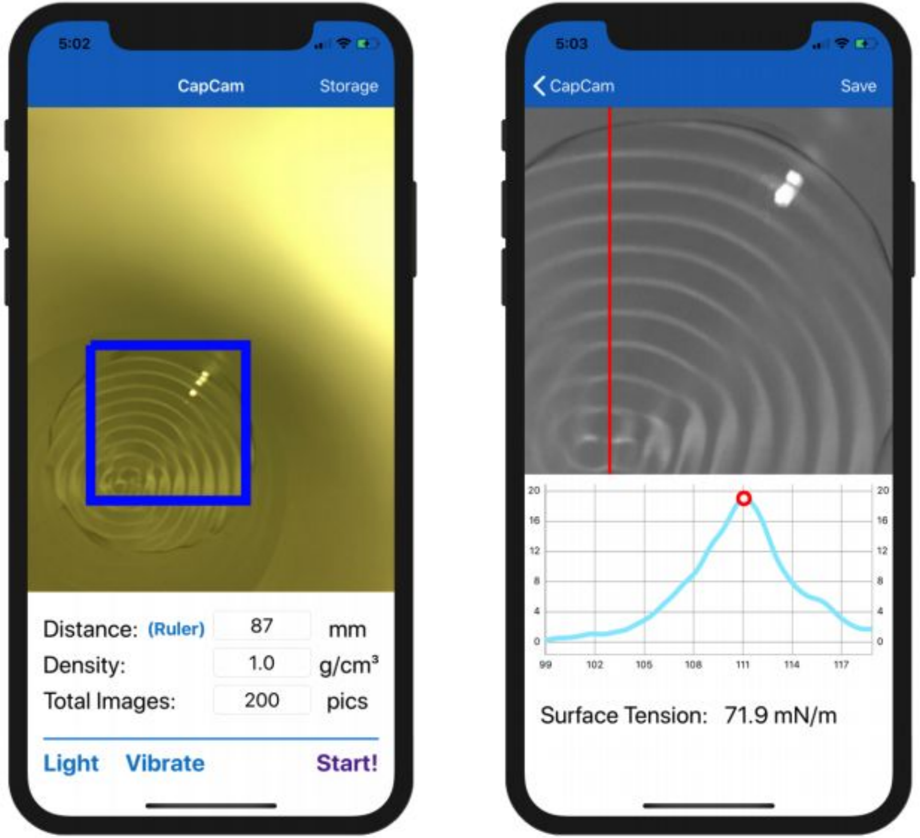


Figure 8: A sample histogram of estimated wavelengths with 200 images.

Interface



(a) Configuration

(b) Analysis

Figure 9: CapCam's User Interface

Experiment - Water Contamination

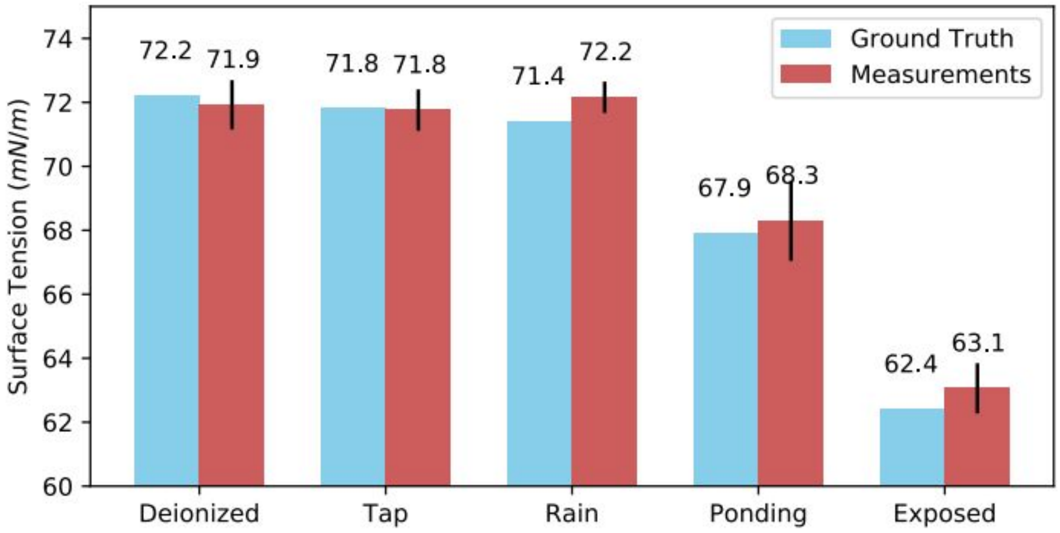


Figure 11: Water Contamination Detection. Both tap water and rain water have a surface tension close to deionized water. In contrast, pond water and exposed water have lower surface tension values due to contamination.

Experiment - Urine Protein Level

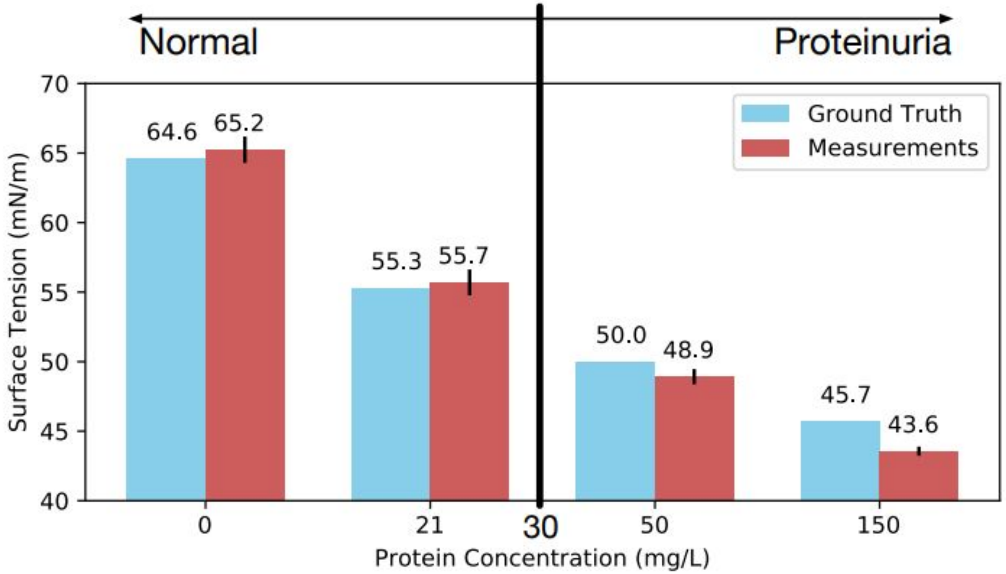


Figure 12: Urine surface tension test with different protein concentration levels. For a healthy person, protein concentration level in urine should be less than $30mg/L$ [16], and the greater the concentration, the higher the risk.

Experiment - Alcohol Concentration

$$TDR = \frac{\gamma}{\rho} = \frac{(2\pi f)^2 - g(2\pi/\lambda)}{(2\pi/\lambda)^3}.$$

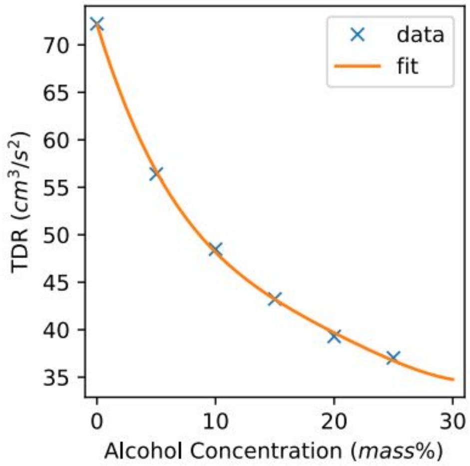


Figure 13: TDR as a function of ethanol concentration. Data points are obtained from Vazquez et al. [33] and Speight et al. [29]. We use a polynomial fit to obtain a continuous function between the concentration level and the TDR.

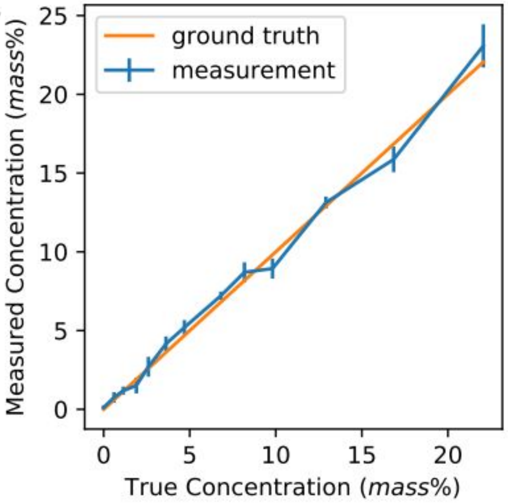


Figure 14: Alcohol concentration as measure by CapCam in blue and ground truth in orange.

Experiment - Depth Ablation

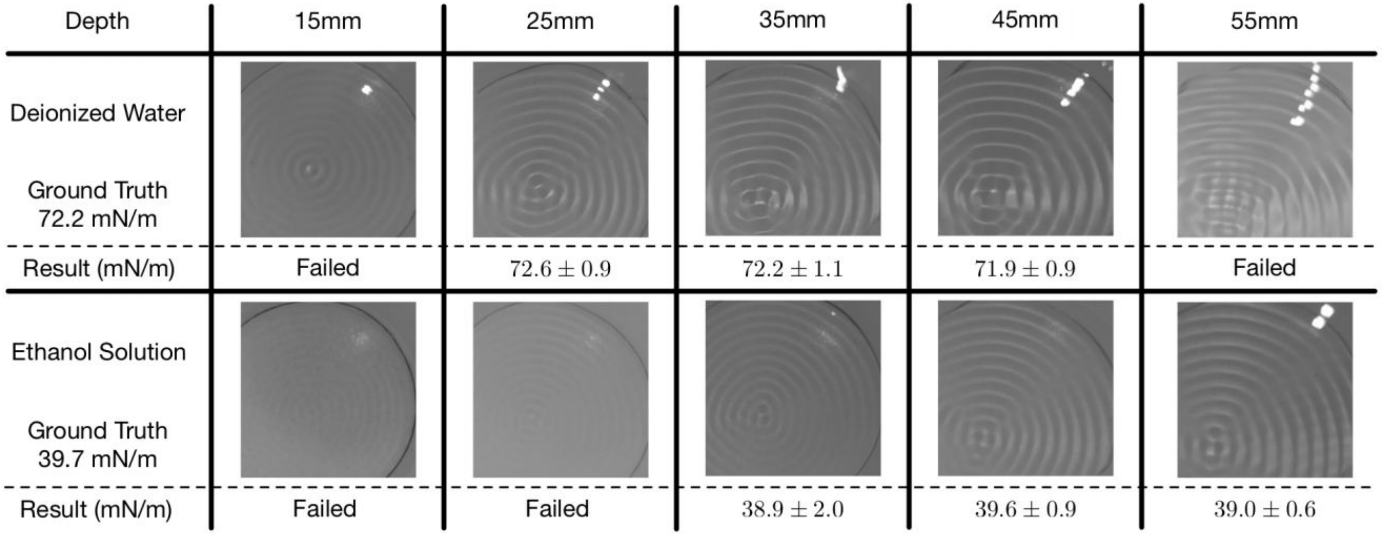


Figure 16: The impact of liquid depth on the quality of the captured image. When the focal length of the waves does not match the depth of the liquid, the bottom of the container may be out of focus. However, as the results indicates, even when the mismatch between the depth and the focal length is about 36% to 40% (20mm out of 55mm for oil and 45mm for water), our system can still measure the surface tension robustly.

Experiment - Container Ablation

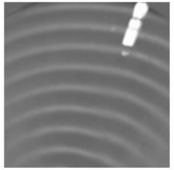
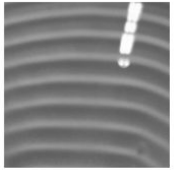
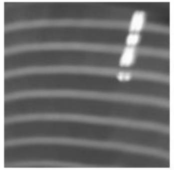
Container Picture			
Dimension	W: 98mm L: 98mm H: 119mm	W: 119mm L: 119mm H: 100mm	W: 140mm L: 140mm H: 90mm
Captured Image			
Result: *Ground Truth 72.2mN/m*	72.0 ± 1.3 mN/m	71.6 ± 1.0 mN/m	72.2 ± 1.1mN/m

Figure 17: Measuring surface tension with different containers. As the figure indicates, CapCam can provide accurate surface tension measurements with different containers without any modification.

Limitations

1. Sensitivity: the inference hasto be taken within the measurement context.
    a. sensitive to bacteria and organic contaminants
    b. Not sensitive to contamination by heavy metal.
2. Container Specification: CapCam has certain requirements on the container type.
    a. the container should have a flat bottom.
    b. the container should be relatively light
    c. circular containers are required.
3. Liquid Transparency: CapCam assumes that the liquid is transparent and the pattern at the bottom is visible from the surface.
4. Phone & Camera Requirements:
    a. New phone models have an API for configuring the camera shutter speed and exposure parameters, and hence our choice of evaluating CapCam on an iPhone X

Citation

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