Three-Dimensional Localization of a Finger in Water Using Human Body Antenna Signals

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***Abstract*—HumTouch is a touch sensing method that leverages the electric currents of the human body generated by AC hum-noise present in the surrounding environment. This sensing principle facilitates the detection of human touch on semiconductive materials. In this study, we demonstrated the localization of a finger in a plastic tank filled with purified water. The currents emitted by the human finger were measured using eight electrodes installed in the tank to estimate the finger's position employing a kernel regression method. The average estimation errors among the three participants were 3.52, 0.55, and 0.72 cm in the depth and the other two orthogonal directions, respectively. The localization errors were negligible in the two-dimensional plane perpendicular to the depth direction; however, they were substantial in the depth direction within the water.**

***Index Terms*—HumTouch, finger sensing, water sensor**

I. Introduction

Touch sensing technologies paly an essential part in our daily lives. Recently, sensing methods capable of turning non-specialized surfaces into touch-sensitive surfaces have garnered the attention in consumer electronics [1]–[5]. One example is an ultrasonic touch sensing system that leverages a strain of ultrasonic waves transferring through a rigid object such as a wall to detect a touch on it [1].

Our research groups have been developing a sensing method referred to as HumTouch [2], [6]–[8] that localizes a human touch on semi-conductive material surfaces by measuring the current leak from a human body reacting to AC hum-noise in buildings. The conductive materials in human bodies, such as minerals, react with these electromagnetic waves and generate currents in our bodies. When a human contact is made with a conductive or semi-conductive object, current leaks from the body into the area in the vicinity of the contacted area. This current can be measured by attaching electrodes to the object and subsequently connecting with data acquisition devices as shown in Fig. 1. Thus far, HumTouch has proven to be available for granite stone [9], paper and wood painted with semi-conductive ink [2], [10].

In this study, we investigated the localization performance of HumTouch when applied to underwater settings. Earlier studies on human monitoring and detection in aquatic environments have relied on camera [11], global navigation satellite systems, and inertial measurement units [12]. By contrast, HumTouch offers an occlusion-free and privacy-preserving method for such purposes compared to previous approaches. In addition, it is particularly suited for use in small-sized water tanks.

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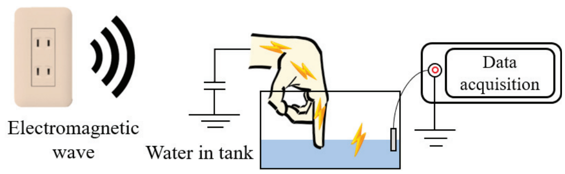

Fig. 1. Principle of HumTouch. The human body reacts with the electromagnetic waves generated from AC power lines. The current leaks into the water and is measured using electrodes in the water. This is used for localization.

In our previous study, we localized a human finger in a plastic tank filled with purified water in one dimension using two electrodes [13]. In this study, we investigated the localization of a human finger under purified water in three-dimensions using eight electrodes in the tank.

II. Apparatus and experimental setting

We filled a plastic tank with purified water (Purified water, TRUSCO, Tokyo, Japan) as shown in Fig. 2. The volume of the water was $37.5 \times 25.0 \times 17.5$ cm^3. It was confirmed that similar results could be acquired using tap water from the western part of Tokyo, Japan. Six locations were marked at three different heights (total 18 locations) at intervals of 7.5 and 9.0 cm along the x and y axes, respectively, as shown in Fig. 2 (b). For the height of the tested locations (z-axis), we selected three levels as follows: 1 cm below the surface level such that only the fingertip was in the water, 11 cm above the bottom such that the entire index finger was in the water, and the bottom of the tank. Eight electrodes were attached at the corners of the tank and connected to two synchronized oscilloscopes (HS6 DIFF, TiePie Engineering, Netherlands; sampling frequency: 500 kHz) to record the signals.

Three participants volunteered for the experiment. The participants removed their shoes and remained still during the experiment to ensure proper connection to the ground. They inserted their index finger into the water and held their fingertip at the designated location for approximately 1 s. Consequently, 18 locations were recorded in one experimental set and five such sets were recorded for each participant.

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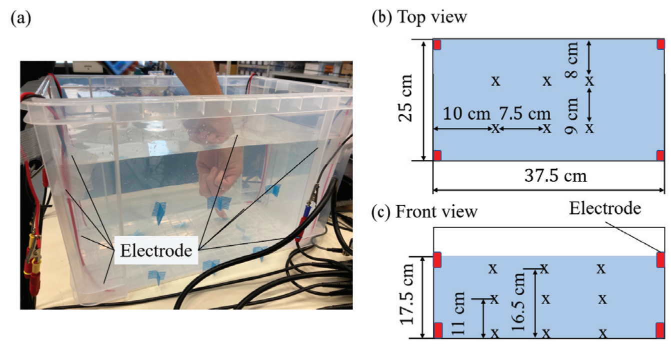

Fig. 2. Experimental setup. (a) Tank filled with purified water and eight electrodes. (b) Top and (c) front view of the tank. Crosses indicate the target points.

III. Kernel Regression Model to Localize the Finger Position

We applied the kernel regression method to estimate the location of the finger in three-dimension. Similar methods were used for the localization on a plane [2], [6]. When the finger is inserted into the water, the recorded maximum voltages are denoted as v_e, where e is the eth electrode. Vector $\boldsymbol{v_s} = (v_1, v_2, ..., v_8)^{\mathrm{T}}$ incorporates the maximum voltages detected by the eight electrodes for sample s. When a voltage set is provided by $\boldsymbol{v_s}$, the corresponding finger position ($\hat{x}$, $\hat{y}$, $\hat{z}$)$^{\mathrm{T}}$ is estimated as follows

$$\begin{bmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{bmatrix} = \begin{bmatrix} \sum_{s=1}^{n} \alpha_{x,s} \mathrm{exp}(-|\boldsymbol{v_s} - \boldsymbol{v}|^2) \\ \sum_{s=1}^{n} \alpha_{y,s} \mathrm{exp}(-|\boldsymbol{v_s} - \boldsymbol{v}|^2) \\ \sum_{s=1}^{n} \alpha_{z,s} \mathrm{exp}(-|\boldsymbol{v_s} - \boldsymbol{v}|^2) \end{bmatrix}, \quad (1)$$

where n is the number of the samples in the learning set and $|.|$ is the L2 norm. The coefficients $\alpha_{x,s}$, $\alpha_{y,s}$, and $\alpha_{z,s}$ are the sth element of the vectors of coefficients $\boldsymbol{\alpha_x}$, $\boldsymbol{\alpha_y}$, and $\boldsymbol{\alpha_z}$, respectively. The vectors of coefficients are computed as follows

$$\begin{bmatrix} \boldsymbol{\alpha_x} \\ \boldsymbol{\alpha_y} \\ \boldsymbol{\alpha_z} \end{bmatrix} = (\boldsymbol{K} + \lambda \boldsymbol{I})^{-1} \begin{bmatrix} \boldsymbol{x} \\ \boldsymbol{y} \\ \boldsymbol{z} \end{bmatrix}. \quad (2)$$

where the vectors $\boldsymbol{x} = (x_1, ..., x_n)^{\mathrm{T}}, \boldsymbol{y} = (y_1, ..., y_n)^{\mathrm{T}}$, and $\boldsymbol{z} = (z_1, ..., z_n)^{\mathrm{T}}$ are the coordinates of the touched locations for the learning samples. The regularization value λ was 0.001 and $\boldsymbol{I}$ was a $n \times n$ unit matrix. Matrix $\boldsymbol{K}$ was computed as follows

$$\boldsymbol{K} = \begin{bmatrix} \mathrm{exp}(-|\boldsymbol{v_1} - \boldsymbol{v_1}|^2) & \dots & \mathrm{exp}(-|\boldsymbol{v_1} - \boldsymbol{v_n}|^2) \\ \vdots & \ddots & \vdots \\ \mathrm{exp}(-|\boldsymbol{v_n} - \boldsymbol{v_1}|^2) & \dots & \mathrm{exp}(-|\boldsymbol{v_n} - \boldsymbol{v_n}|^2) \end{bmatrix}. \quad (3)$$

IV. Results

To evaluate the localization performance, we applied the leave-one-out cross validation. For each participant, four out of five sample sets were used to construct the regression model, and the model was tested using the remaining sample set. This procedure was iterated five times for each participant. Fig. 3 shows the mean estimated locations among the five trials for the three participants. The average estimation errors for P1, P2, and P3 were 1.98, 1.41, and 1.80 cm, respectively. For P1, the mean estimation errors along the x, y, and z directions were 1.21, 0.60, and 4.12 cm, respectively. Further, for P2, they were 0.66, 0.91, and 2.65 cm, respectively. Finally, for P3, they were 0.99, 0.64, and 3.79 cm, respectively.

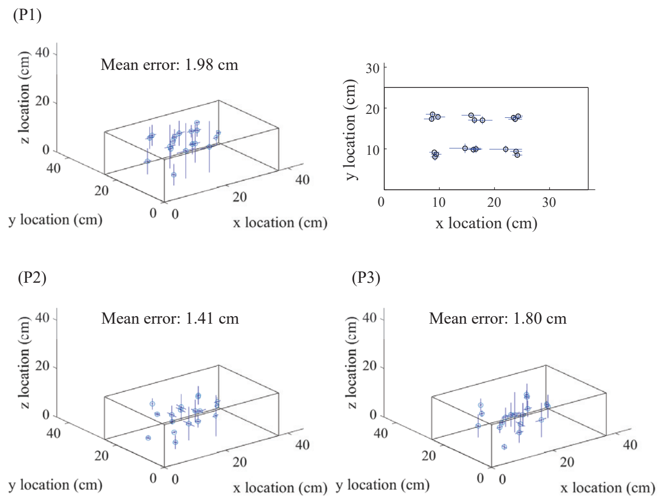

Fig. 3. Results of localization for participants P1, P2, and P3. The figure at the top right presents a top view of the results for P1. The black lines indicate the boundary of the water. The points and error bars indicate the means and standard deviations of the estimates, respectively.

V. Conclusion

In this study, we presented a method for localizing a human finger while submerged underwater at 18 distinct locations. The results indicate that the mean estimation errors were less than 1.0 cm in both the x and y directions, implying that finger localization can be achieved with an error margin smaller than the size of a fingertip. However, in the longitudinal or depth direction of the finger, the mean localization error was determined to be 3.52 cm. This finding implies that localizing the tip of elongated human body segments such as fingers using the methodology employed in this study may present a challenging task.

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