Proximity Distance Estimation based on Capacitive Coupling between 1mm^3 Sensor Nodes

Tatsuya Shinada Masanori Hashimoto Takao Onoye
Dept. Information Systems Engineering, Osaka University
Email: hasimoto@ist.osaka-u.ac.jp

Abstract— **We are working toward actualizing a real-time 3D modeling system. It uses a sensor network that distributes many 1 mm^3-class sensor nodes in plastic clay. The distributed sensors sense distances between them, and the sensor network collects the distance information for recognizing object shape by calculating relative positions of nodes based on the collected node-to-node distances. This paper proposes a distance estimation method based on capacitive coupling between sensor nodes for the 3D modeling system. An electrical signal is transmitted through a closed loop composed of node-to-node capacitive coupling, and the signal attenuation is used for the distance estimation. We investigate gain and directivity of the signal transmission with electric field and circuit simulation to explore appropriate electrode designs for the proposed method and evaluate the feasibility of the node localization with the proposed distance estimation method.**

I. INTRODUCTION

Services and applications using 3D model are becoming popular thanks to advances in information technology, and 3D computer graphics for entertainments and 3D CAD for architecture design, for example, are widely used. 3D modeling software for PC is now commercially available. However, its usage is still not easy for most of people. An intuitive and easy way of 3D modeling for non-expert people is demanded.

An approach for this purpose is that a person creates a physical shape with such as clay and captures its shape with a 3D scanner. An advantage of this approach is relatively easier usage. However, it needs a certain amount of time before obtaining the shape on a computer since 3D scanning is not so fast. This could degrade modeling efficiency since turn-around-time between physical shape modification and reproduction on a computer is quite long. There are a few researches on tangible computer interfaces for 3D modeling [1], but they have not been put to practical use.

To enable intuitive real-time 3D modeling, we have devised a concept called “iClay” as illustrated in Fig. 1 and are working for its actualization. In this iClay system, a number of 1mm^3-class tiny sensor nodes are distributed in plastic clay and they organize a wireless sensor network. Each sensor node senses distances to adjacent nodes and these distance information is collected to a computer. The computer calculates relative node positions and reproduces the 3D object based on the distance information. 2D node localization is widely studied in sensor network area, and a few studies are also reported for 3D localization [2]. Energy is wirelessly transmitted to each sensor node for eliminating battery exchange. The expected advantages of this approach are occlusion-free shape acquisition and real-time object reproduction, which cannot be achieved by conventional approaches using laser range finder or cameras.

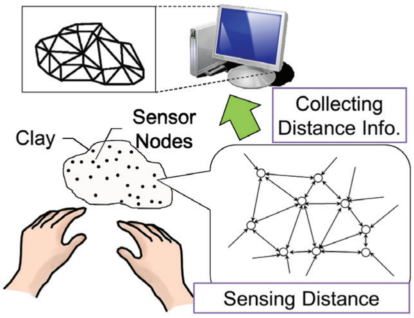

Fig. 1. “iClay” concept for real-time 3D shape acquisition.

This paper focuses on the sensor to sense distances to adjacent nodes and proposes a distance estimation method that uses a signal transmission through capacitive coupling between nodes. We discuss its distance estimation accuracy assuming various electrode configurations through electro-magnetic and circuit simulations. In addition, we experimentally confirm that 3D node localization is possible even with the distance estimation error.

II. PROPOSED DISTANCE ESTIMATION METHOD

In iClay system, proximity sensing for all directions in the clay is required for the embedded sensor nodes. Table I lists existing distance estimation methods. TOA (time of arrival), TDOA (time difference arrival) and RSSI (received signal strength indication), which are often used in wireless sensor networks, are not capable of the mm-scale proximity sensing of interest due to a requirement for highly accurate time synchronization and indistinguishable small attenuation in short distance. Distance estimation methods based on light and ultrasonic are not suitable for a solid object in which obstacles (nodes) are densely buried. Methods using eddy current and capacitive coupling could have a possibility to be used, but proximity sensing methods readily applicable to iClay system are not available, as far as the authors.

This paper proposes a distance sensing method that estimates node-to-node distance based on the amplitude of a propagated signal through capacitive coupling between sensor nodes. Figure 2 illustrates the overview of the proposed

978-1-4799-0620-8/13/$31.00

TABLE I

EXISTING DISTANCE SENSING METHODS.

Method	Principle	Problem
Wireless TOA· TDOA	Prop. time	Proximity sensing difficult
Wireless RSSI	Attenuation	Proximity sensing difficult
Light	Reflection	Not propagate in clay
Ultrasonic	Reflection	Weak to obstacles
Eddy current	Mag. field	Strong directivity
Cap. coupling	Elec. field	Not studied enough

method. TX (transmitter) node injects a pulse signal representing TX node ID to the electrode of TX node, RX (receiver) node receives the signal, and its amplitude is digitized by an A/D converter. A set of data consisting of TX node ID, RX node ID and the digitized amplitude is delivered to a computer, and the computer estimates the node-to-node distance. The most significant feature of this method is that the amplitude changes in a short range since the capacitance value varies sensitively in such proximity range. Solid object is not a problem for the proposed method. Another feature is that quasi-static electric field, which is used in the proposed method, tends to have less directivity compared to magnetic field.

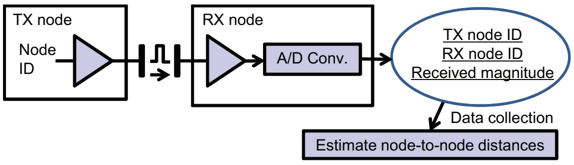

Fig. 2. Proposed distance estimation method.

Communication using electrical filed is widely studied for BAN (body area network) [3], which originates from PAN (personal area network) proposed by Zemmerman of IBM in 1996 [4]. BAN is responsible for collecting personal biological information from sensors on and in the body, and the collected information is utilized for health management and care. BAN is largely classified into WBAN (wireless body area network), which uses electro-magnetic wave in UHF band, and IBC (intra-body communication), which uses the human body as a signal transmission medium. The latter IBC has several advantages. For example, it has less interference with other electric devices since the signal is confined within the body. In addition, usable frequency range is wider, and less power is consumed thanks to less signal attenuation. IBC has two types; galvanic type and electric field type. The electric filed type uses capacitive coupling between node and human body, which will be hereafter called EF (electric field) communication.

In this EF communication, each of TX and RX has two electrodes of SIG and GND, and a loop path is organized consisting of SIG electrode of TX, capacitive coupling, body, capacitive coupling, SIG electrode of RX, GND electrode of RX, capacitive coupling, (earth, capacitive coupling) and GND electrode of TX in this sequence. This loop is indispensable for signal transmission, since it is in quasi-static electrical field and a signal is not propagating as an electromagnetic wave. The proposed distance estimation method also uses EF communication, and hence the proposed node-to-node communication need to construct a closed loop including a return path as shown in Fig. 3. For this purpose, each node should have two electrodes of SIG and GND within 1mm^3 volume. The following sections investigate the signal transmission characteristics with various configurations of two electrodes, and evaluate the feasibility of iClay system through 3D node localization experiments taking into account the possible accuracy of the proposed method.

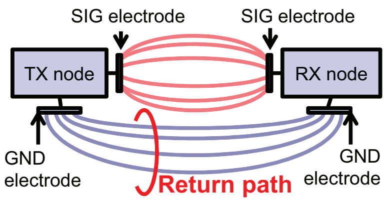

Fig. 3. Paired electrodes of SIG and GND for composing a closed loop.

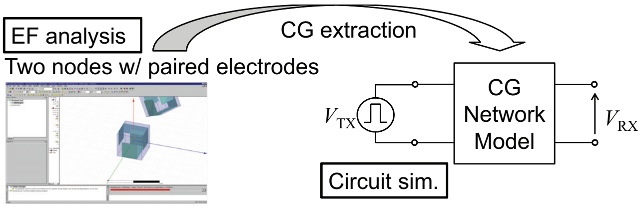

Fig. 4. Simulation overview.

III. EXPERIMENTAL EVALUATION OF ELECTRODE CONFIGURATION

This section evaluates characteristics of single-node-to-single-node communication through simulation.

A. Evaluation setup

Figure 4 shows the simulation overview. The simulation consists of EF analysis obtaining parasitic elements between electrodes and pulse propagation analysis with circuit simulation. ANSYS Q3D extractor is used for EF analysis, where Q3D can compute LCRG (inductance, capacitance, resistance and conductance) of parasitic elements by solving a model defined by structural and material information with boundary element method. In our EF analysis, C and G between electrodes and CG between electrode and point at infinity are extracted to compose a CG network model. Then, Synopsis HSPICE circuit simulator evaluates the output voltage using the CG network model in case that a pulse is injected.

As the characteristics of signal transmission, directivity and gain are examined, where gain is defined as the ratio of output voltage V_{RX} to input voltage V_{TX}. The metric of directivity will be explained later. Higher gain contributes to power reduction and sensitivity improvement of sensors, and the weak directivity is required for distance estimation in all directions. Weaker directivity improves the accuracy of distance estimation.

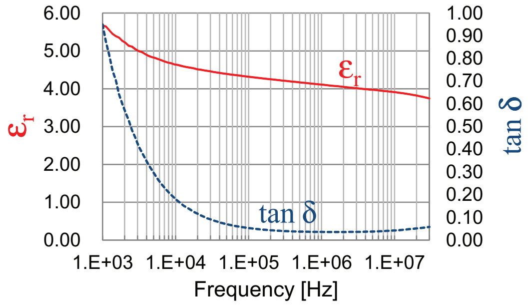

Fig. 5. Measured σ_r and tan δ of resin clay.

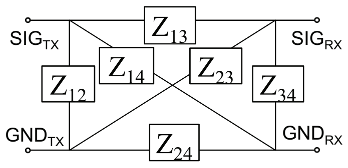

Fig. 6. Equivalent circuit for CG network model. Impedances to point of infinity are omitted.

We set relative dielectric constant (ϵ_r) and dielectric loss tangent (tan δ) of clay to 4.0 and 0.04. These numbers come from our measurement result of resin clay shown in Fig. 5 assuming 1 MHz. A 1 MHz square wave is given from the voltage source in circuit simulation.

Figure 6 represents an equivalent circuit of CG network model. This equivalent circuit omits capacitances and conductances to point of infinity for simplifying the following discussion. It should be noted that capacitances and conductances to point of infinity are considered in circuit simulation. Supposing a voltage source whose amplitude is V_{TX} is connected between $\mathrm{SIG_{TX}}$ and $\mathrm{GND_{TX}}$, V_{RX}, which is the voltage between $\mathrm{SIG_{RX}}$ and $\mathrm{GND_{RX}}$, can be analytically derived by solving a closed circuit equation. Consequently gain $Ga(= V_{\mathrm{RX}}/V_{\mathrm{TX}})$ is expressed by

$$Ga = \frac{Z_{34}(Z_{14}Z_{23} - Z_{13}Z_{24})}{Z_{13}Z_{23}(Z_{14}+Z_{24}) + Z_{14}Z_{24}(Z_{13}+Z_{23}) + (Z_{13}+Z_{23})(Z_{14}+Z_{24})Z_{34}}. \tag{1}$$

Equation (1) indicates that Ga is sensitive to Z_{34} between SIG and GND electrodes at RX node. In addition, when the symmetry between SIG and GND electrodes deteriorates, the term of $Z_{14}Z_{23} - Z_{13}Z_{24}$ becomes smaller, which results in smaller Ga. Therefore, to maximize Ga, we should use symmetric SIG and GND electrodes and minimize the capacitance between these two electrodes. Taking into account these findings, we selected a set of electrode configurations shown in Fig. 7. SIG and GND electrodes are put on the surfaces of the cube for maximizing the distance between them. In config 0 and 1, each electrode occupies a single face. Each electrode of config 2 and 3 uses two faces, and that of config 4 and 5 uses three faces.

Figure 8 illustrates the setup of EF analysis. To evaluate the directivity of each electrode configuration, we fix a TX node at the center, and move and rotate the RX node for making a variety of their relative placements. The movement and rotation of RX node are expressed by six parameters of (r, θ, ϕ) and (α, β, γ). r is varied from 1.75 mm, which is the minimum distance for non-overlapping, to 10 mm, and θ, ϕ, α, β and γ are set to $n\pi/6 < 2\pi$ $(n = 1, 2, \ldots)$ independently.

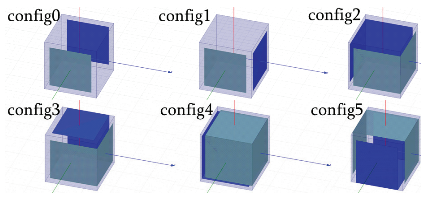

Fig. 7. A set of electrode configurations.

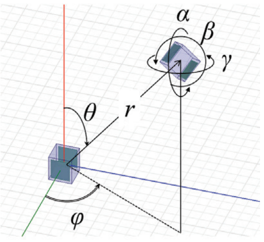

Fig. 8. Relative placement of TX and RX nodes.

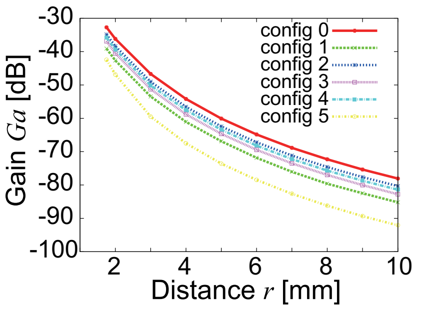

Fig. 9. Simulation results of gain Ga).

Let us explain a metric for evaluating directivity. The problem of directivity is that it induces uncertainty in V_{RX} and degrades distance estimation accuracy. Here, this uncertainty in V_{RX} can be translated into distance uncertainty (σ_r), which corresponds to distance estimation error, as follows.

$$\sigma_r = \frac{\sigma_V}{dV_{\mathrm{RX}}^{\mathrm{avg}}/dr}, \tag{2}$$

where σ_V is the standard deviation and $V_{\mathrm{RX}}^{\mathrm{avg}}$ is the average of V_{RX} at each distance r for various sets of θ, ϕ, α, β and γ. This σ_r is used as the metric of the directivity and smaller σ_r is desirable. This equation tells us that the distance estimation error becomes small when $dV_{\mathrm{RX}}^{\mathrm{avg}}/dr$ is large.

B. Experimental results

Simulation results of Ga and σ_r are shown in Figs. 9 and 10, respectively. It is observed that the received voltage, which corresponds to Ga for the fixed input voltage, is roughly proportional to $1/r^3$. Simpler face-to-face configurations of electrodes, such as config 0, 2, and 4, attain higher gain. In contrary, gains of config 1, 3, and 5 decrease since the region where two electrodes are adjacent becomes larger and then the capacitance between SIG and GND nodes becomes larger.

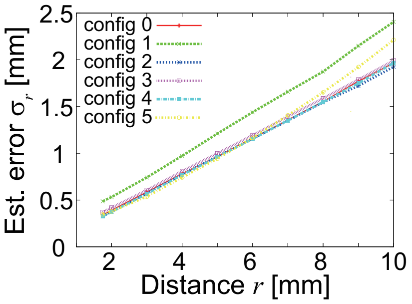

Fig. 10. Simulation results of distance estimation error σ_r.

On the other hand, the distance estimation error σ_r is similar for most of configurations, while σ_r of config 1 is worse. In config 5, σ_r is the smallest in short distance range, while it increases more rapidly as r becomes larger. This tendency of config 5 is thought to originate from its lower gain.

We also evaluated Ga and σ_r for various size of electrodes while keeping the volume of node 1 mm^3. In addition, we changed the relative dielectric constant inside the node to 1.0 instead of 4.0. We observed that these modifications affect not only Ga but also σ_V considerably, and they are in a trade-off relationship. As a result, distance estimation accuracy σ_r is roughly unchanged even though these modifications are given. Detailed results are omitted here due to space limitation.

IV. REPRODUCING NODE POSITIONS

This section investigates the feasibility of node localization using the proposed distance estimation method. This experiment assumes the distance estimation error is expressed by

$$\sigma_r = 0.1932r - 0.0061 \quad [\text{mm}]. \qquad (3)$$

This first order expression is obtained from the results in Section III-B. The distance error is randomly given to each node-to-node pair assuming that the distance error follows a normal distribution whose standard deviation is σ_r.

We implemented a program that localizes nodes using node-to-node distance information. This program first selects arbitrary four nodes and assigns coordinates. After that, nodes are sequentially localized one-by-one using the information of nodes already localized. This sequential localization, however, has a problem. Once a flipping mistake happens due to indeterminacy, it is likely that nodes localized after this mistake have larger localization error or localization itself becomes impossible. To minimize this problem, [2] proposes an approach that a robust set of nodes which are less likely to cause fatal mistakes are first searched, and they are used for node localization. This concept of robust node set is first proposed by Moore for 2D problem [5] and it is extended to 3D problem in [2].

Experiments of node localization are carried out for a 50x50x50 mm^3 clay in which 375 nodes are randomly distributed. This node density was selected according to a preliminary experiment that investigated the necessary node density for localization. Experimental results of node localization are shown in Figs. 11 and 12. The maximum sensible distance is changed in the experiments and it corresponds to the x-axis. The y-axis of Fig. 11 represents the ratio of localized nodes. The y-axis of Fig. 12 is the average distance between the estimated position and the actual position.

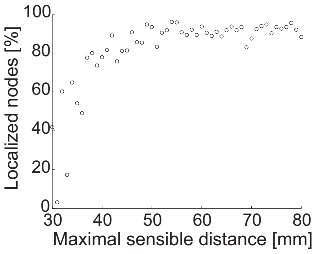

Fig. 11. Ratio of localized nodes.

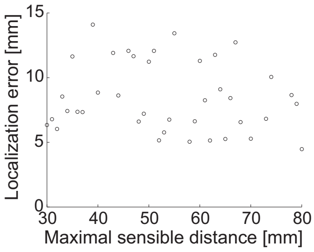

Fig. 12. Average localization error.

This result shows that the 90 % nodes can be localized by using the proposed distance estimation method even though the distance estimation error of Eq. (3) exists as long as the maximum sensible distance is larger than 50 mm. The node localization becomes possible even with the shorter maximum sensible distance by increasing the node density. The average position error of over 5 mm is larger than our expectation. However, this number could happen even when the relative positions are reasonably reconstructed. This is because the origin is set by the first four nodes and the shift and rotation of the object easily increase this average localization error. Further investigation is necessary.

We finally carry out the node localization by changing the slope of Eq. (3). The result show that the node localization becomes impossible when the slope is larger than 0.2. This means that the distance estimation error of Eq. (3) is close to this upper boundary. Ideas to reduce the estimation error are demanded.

V. CONCLUSION

This paper proposed a distance estimation method suitable for proximity region. The proposed method estimates the node-to-node distance according to the voltage magnitude of a signal propagated through capacitive coupling. The achievable distance estimation accuracy is experimentally evaluated with various configurations of paired electrodes. We also carried out node localization experiments with the error model of the proposed method, and showed that 90% of nodes can be localized.

REFERENCES

[1] Michael Reed, “Prototyping Digital Clay as an Active Material,” in Proc. International Conference on Tangible and Embedded Interaction, pp.339–342, 2009.

[2] R. Mautz, W. Ochieng, G. Brodin, and A. Kemp, “3D Wireless Network Localization from Inconsistent Distance Observations,” *Ad Hoc & Sensor Wireless Networks*, vol.3, no.2–3, pp. 141–170, 2007.

[3] R. Kohno, K. Hamaguchi, H. Li, and K. Takizawa, “R& D and Standardization of Body Area Network (BAN) for Medical Healthcare,” *Proc. International Conference on Ultra-Wideband*, vol. 3, pp.5–8, 2008.

[4] T. G. Zimmerman, “Personal Area Networks:Near-Field Intrabody Communication,” *IBM System Journal*, vol. 35, no. 3–4, pp.609–617, 1996.

[5] D. Moore, J. Leonard, D. Rus, and S. Teller, “Robust Distributed Network Localization with Noisy Rangemeasurements,” *Proc. ACM Symposium on Networked Embedded Systems*, 2004.