Toward Real-time 3D Modeling System with Cubic-Millimeters Wireless Sensor Nodes

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***Abstract*—We are working toward actualizing a real-time 3D modeling system called iClay. This modeling system uses a sensor network that distributes many 1mm^3-class sensor nodes in plastic clay. The distributed sensors sense the distances between them, and the sensor network collects the node-to-node distance information to recognize the clay shape by node localization. This paper first reviews fundamental technologies necessary for developing the iClay system and introduce the current status of the development. Next, we focus on a wireless transmitter, which is one of the key technologies for the iClay system, and presents a compact OOK transmitter that uses coils for radiation as well as oscillation, eliminating the need for an external antenna. The prototyped the transmitter with 2.8 mm × 2.8 mm × 4.2 mm volume achieves 205 pJ/b at 1 Mbps communication.**

I. Introduction

With advancement in hardware and IT technology, 3D models are used to improve user experience not only in professional services/contents but also semi-professional or even amateur ones. For supporting 3D modeling, a number of commercial 3D modeling software is available. On the other hand, since 3D modeling is first established for professional use, that software is designed for professionals regarding performance and usability, and hence it is not suitable for most of the people. An intuitive scheme of 3D modeling is demanded by non-expert people.

Aggressive VLSI technology advancement enables signal processing and computation in a small volume like cubic-millimeter [1], [2]. Such small size computation can be embedded anywhere, which can contribute to new human-computer interaction in IoT (Internet of Things) era. On the other hand, for implementing applications, the computing device needs to receive power, sense signals and transmit processed signals. These power supply, sensing, and signal transmission are all challenging since the volume is tiny and the numbers and performance of electrodes and antennas are highly limited.

As an application of small volume computation, we have proposed a concept named “iClay” (Fig. 1) [3]. The iClay system is supposed to provide instant real-time 3D modeling with the clay, in which small sensor nodes are embedded. Through the sensor network consisting of sensor nodes and a host computer, the distance information between sensor nodes is collected, and the clay shape is reconstructed based on the distance information. The advantage of iClay system is that users can construct a 3D model by touching an actual object in real-time. This advantage makes it possible for users to

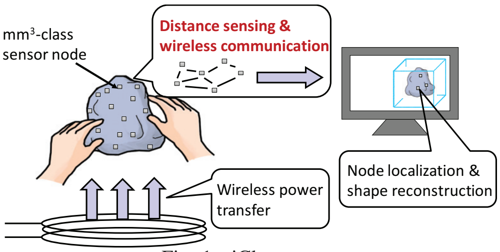

Fig. 1. iClay system.

concentrate on the shape construction without being bothered by software manipulation. With this advantage iClay system is intended to be used for, for example, kids interactive education and rehabilitation training for brain disease patients.

This paper first explains the difficulties in implementing small sensor nodes for iClay and introduces our achievements on fundamental technologies for actuating iClay system. Then, we present a dedicated antenna less wireless transmitter suitable for the small volume implementation.

II. iClay System

The iClay system in Fig. 1 aims to enable simple and real-time 3D modeling for interaction-oriented applications, and its interface consists of clay embedded with many small sensor nodes. Each node embedded in the clay receives power wirelessly, measures the distance between neighboring nodes and transmits the distance information to the host computer through the wireless sensor network. The host computer estimates the shape of the clay from the inter-node distance information collected through the network. As a result, the user can input the three-dimensional shape to the computer only by deforming the clay. For actuating iClay system, consequently, we have to establish wireless power supply, wireless communication, distance sensing to adjacent sensor nodes, and clay shape reconstruction.

For shape reconstruction, a cross-entropy based node localization method is developed, and its parallel computation efficiency is presented in [4]. Furthermore, GPU implementation is presented in [5]. Fig. 2 shows the speed-up thanks to GPU implementation [5] compared to 80-CPU implementation [4]. Even with 80-CPU computation, 61.5X computational time reduction is achieved, which makes contributes to real-time shape reconstruction. Fig. 3 exemplifies 3D shapes reconstructed by the proposed node localization [5]. We can see

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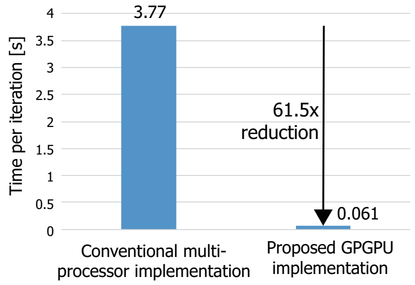

Fig. 2. Acceleration thanks to GPU implementation of 3D node localization.

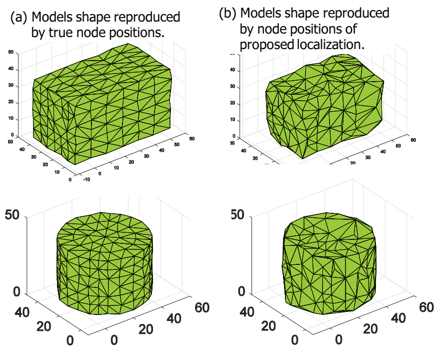

Fig. 3. Shapes reconstructed by node localization.

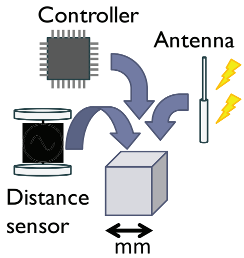

Fig. 4. Difficulty in integrating multiple devices into a small volume.

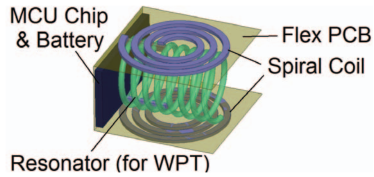

Fig. 5. Accommodating helical coil resonator for wireless power transfer and proposed dual-use antenna in a sensor node [9].

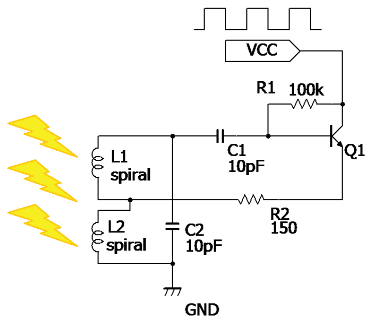

Fig. 6. Proposed transmitter.

that the shapes are well reconstructed from the information on the node-to-node distance only in the neighborhood.

As for wireless power transmission, Ref. [6] demonstrated wireless power transfer of 450 μW to a 50mm^3 node, where the majority of the volume consists of helical coil resonator. Ref. [7] discusses the coil design at the power transmitter side and designs a wireless power transfer system, and Ref. [8] presents an impedance matching technique in magnetic-coupling-resonance wireless power transfer system.

A difficulty in the sensor node implementation is to integrate all the functionalities into a small volume, i.e. the mm-cubic node needs to accommodate antenna, distance sensor, controller, etc., as illustrated in Fig. 4. To mitigate this problem, Ref. [9] presents a mm^3-class dual-use near-field antenna that can be used for both magnetic-field based communication and electrical-field based distance sensing. The proposed dual-use antenna can be accommodated in sensor node consistently with the helical coil resonator as depicted in Fig. 5. The proposed antenna is printed on a flexible PCB and connected to transmitters mounted on the flexible PCB. Furthermore, Ref. [10] proposes a simple VHF band transmitter that uses two inductors both for oscillation and radiation, which makes the dedicated external antenna unnecessary. This transmitter will be introduced in the next section.

III. Dedicate Antenna Less Wireless Transmitter

Integrating a high-performance transmitter in extremely small nodes is difficult since the resonant frequency of the tiny antenna is very high and the radiation performance degrades. On the other hand, fortunately, the high communication speed is not demanded in most of IoT applications, especially for small volume sensor nodes. Device cost is rather more important than performance. Another key requirement is low power operation since each node is expected to operate for a long time with a compact and small capacity battery. Even when the power is wirelessly provided, and the transmitter operates intermittently, the amount of energy stored in such a small volume is highly limited, and low energy operation is indispensable. From the above, the following features are required for small wireless nodes for IoT.

- Small volume
- Low cost
- Low energy per bit
- Low standby power

This section presents a simple VHF band transmitter that uses two inductors both for oscillation and radiation. The proposed transmitter does not use a dedicated 50Ω antenna, and hence the impedance matching is unnecessary. These features are helpful for reducing the number of components and consequently the volume and cost. As for the power, we develop a scheme that minimizes the dead-time of on-off keying (OOK) for improving the communication speed and reducing energy per bit. For achieving low standby power, the proposed transmitter can be completely turned off in the sleep mode. To demonstrate the performance, we made a 2.8 $\times$ 2.8 $\times$ 4.2 mm^3 prototype of the proposed transmitter using discrete devices. Experimental results show that the transmitter achieved 1 Mbps communication for 1m distance at 1.0V supply voltage. In this case, the energy consumption per bit is 205 pJ / bit.

A. Proposed Transmitter and Implementation

Fig. 6 shows the schematic of the proposed transmitter. The transmitter is based on a collector-grounded type Hartley

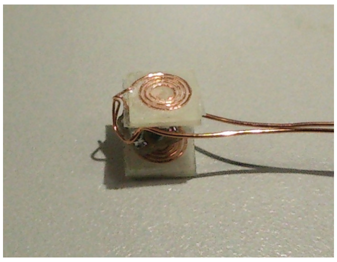

Fig. 7. Prototype of proposed transmitter.

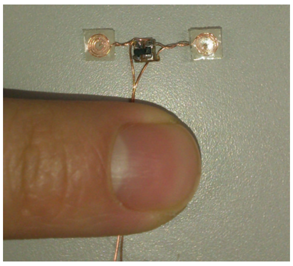

Fig. 8. Expanded view of prototype.

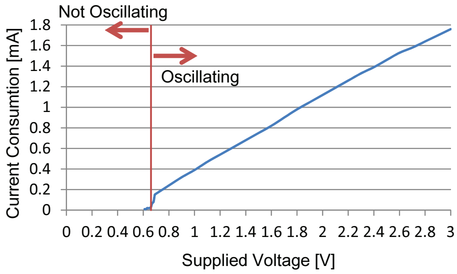

Fig. 9. Current consumption versus supply voltage.

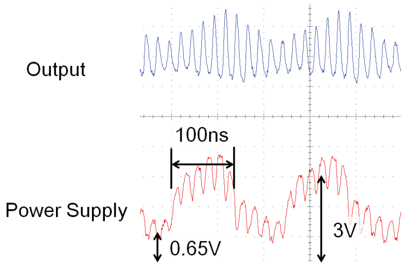

Fig. 10. Transmitter output for 3 V, 20 Mbps communication.

oscillator circuit that includes two coils for LC oscillation. In the proposed transmitter radiates electromagnetic waves from these two coils instead of a dedicated external antenna. Let us explain the basic operation of the Hartley oscillator. Q1 in the schematic is a VHF/UHF band transistor and is used as a current amplifier. When a signal is applied to the base of Q1, a current-amplified same-phase signal arises at the emitter. By injecting the current-amplified signal into the tap of the coil, a positive feedback circuit is composed and starts to oscillate. Also, the signals other than the resonance frequency are attenuated by the tuning circuit consisting of L1, L2, and C2, and then this circuit outputs a sine wave at the resonance frequency.

OOK modulation is accomplished by powering on or turning off the oscillator as depicted in Fig. 6. A short time later after the power-on, After the power-on, the oscillation, i.e. “ 1 ” radiation starts a short time later. This duration between the power-on and the oscillation start is a wasteful time for OOK and this dead-time limits the maximum communication throughput since the symbol time cannot be smaller than this dead-time. To improve the throughput, this dead-time should be minimized. Also, the dead-time minimization is helpful to reduce the energy since the signal transmission finishes in a shorter time.

This dead-time originates from the coil inductance. When the transmitter is powered on, the inductor generates counter electromotive force and then the coil cannot conduct current immediately after the power-on. From another point of view, in the case that non-zero current is flowing in the coil beforehand, the generated counter electromotive force can be mitigated. Consequently, the current necessary for oscillation begins to flow earlier and the dead-time becomes shorter. This non-zero current is provided by giving voltage V_{mid} as VCC during “0” transmission. Note that the oscillator is not oscillating at V_{mid}. We need to determine V_{mid} taking into account the trade-off between the dead-time reduction and power consumption during “0” transmission.

Figs. 7 and 8 show the prototype of the proposed transmitter. 1.6 mm × 0.8 mm chip resistors and capacitors are used for the prototype. The size of the transistor Q1 is 1.6 mm × 1.6 mm.

B. Evaluation

Fig. 9 shows the current consumption of the transmitter when the power supply voltage is varied from 0.6 V to 3 V. The red vertical line in the figure corresponds to 0.66 V, which is the minimum voltage required to start oscillation. The proposed transmitter can operate at a wide range of supply voltage. Fig. 9 also shows that the current rapidly increases when the power supply voltage exceeds 0.65 V, where 0.65 V is the base-emitter saturation voltage of Q1. Beyond 0.7V, the current is proportional to the power supply voltage, which is due to the following reason. Transistor Q1 operates in forward active mode. In this case, the collector current is kept constant even with the collector potential variation as long as the base current is constant. On the other hand, the circuit in Fig. 6 is a fixed bias type circuit. The base current is proportional to the collector potential, and the collector current is proportional to the base current. Consequently, the collector current becomes proportional to the collector potential, i.e. VCC.

When powering on the transmitter, the oscillation starts after a certain amount of dead-time. In the original design, 400 ns dead-time is necessary, and this dead-time limits the throughput. According to Fig. 9, V_{mid} is set to 0.65 V, where it is the maximum voltage that cannot start the oscillation. The current at 0.65 V is 0.02 mA, and it is negligible compared to the current during “1”. Thanks to this, the dead-time is reduced to 40 ns, which is 1 / 10 or less compared to 0 V to 3 V transition. This reduction means that the maximum throughput is expected to improve by 10X. This shorter dead-time can contribute to the throughput improvement. Fig. 10 shows that 20 Mbps transmission is feasible at 3 V operation thanks to the shortened dead-time.

Finally, the communication speed including both the transmitter and receiver was evaluated by observing the output of the FM front end circuit with an oscilloscope. A rectangular wave with 50% duty ratio was given from a function generator to the proposed transmitter as VCC, and the maximum frequency at which the waveform could be reproduced on the

TABLE I
Transmission Range vs Communication Speed.

Range [m]	Communication speed[Mbps] (Energy per bit) 1V	2V	3V
1	1.0 (205pJ/b)	3.0 (380pJ/b)	3.0 (890pJ/b)
5	0.8 (256pJ/b)	1.4 (814pJ/b)	1.4 (1910pJ/b)

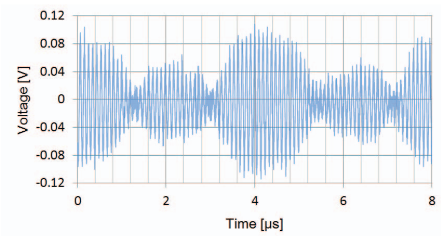

Fig. 11. Waveform at receiver in case of 1Mbps communication.

TABLE II
Comparison with related works.

	[11]	[12]	[13]	This Work (1V)	This Work (2V)
Implementation	CMOS 130nm	CMOS 180nm	CMOS 130nm	discrete components	
Antenna	ext	ext	ext	int	
Power (mW)	2.7	0.7	1.68	0.39	2.24
Modulation	2FSK	2FSK	2FSK	OOK	
Data rate	48kbps	5Mbps	4Mbps	1Mbps	3Mbps
Energy/bit(nJ/b)	56.25	0.14	0.42	0.205	0.38

oscilloscope was evaluated. Three supply voltages of 1, 2 and 3V and two distances of 1 m and 5m between the transmitter and receiver were tested. Results are listed in Table I. This table also includes energy per bit under each condition. As for 1 m, the supply voltages of 1 V achieved 1.0Mbps, and of 2, and 3V achieved 3.0 Mbps throughputs. The lowest energy per bit of 205 pJ/bit was attained at 1 V. Fig. 11 shows the waveform at the receiver when a 500 kHz, i.e., 1 Mbps, signal is transmitted by the transmitter operating at 1 V with 1 m distance. We can see the intermediate frequency of 10 MHz is amplitude-modulated at 500kHz. In this case, the power consumption per bit is 205 pJ / bit. It should be noted that the throughput in each condition depends on the receiver performance and, with a more sophisticated receiver, the energy per bit could be further reduced, which is one of our future works.

The measurement results of the proposed structure are summarized in Table II. Table II also shows comparisons with related studies on small transmitters. We can see that the proposed transmitter achieved better throughput and energy per bit than [11] and comparable performance to [12] [13] without any dedicated external antenna. This comparison clarifies that the coils used for LC oscillation can also be utilized for electromagnetic wave radiation. The proposed transmitter needs no impedance matching, and hence it is suitable for smaller volume implementation.

IV. Conclusion

This paper introduced the iClay system and recent works on shape reconstruction, wireless power transmission, distance sensing and wireless power transmission. Also, we presented an OOK transmitter that used coils for radiation as well as oscillation, eliminating the need for an external antenna. This feature makes it possible to reduce the number of components, resulting in volume and improving the compatibility with iClay node implementation. The prototyped transmitter at 1 Mbps communication was 205 pJ/bit at 1 Mbps communication. We are developing a prototype that includes all the functionalities demanded as iClay sensor nodes. VLSI implementation of the transmitter is also one of the future works.

Acknowledgements

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