A Swallowable Sensing Device Platform with Wireless Power Feeding and Chemical Reaction Actuator

Ryota Nakamura, *Student member, IEEE*, Shintaro Izumi, *Member, IEEE*, Hiroshi Kawaguchi, *Member, IEEE*, Hidetoshi Ohta, *Member, IEEE*, and Masahiko Yoshimoto, *Member*, *IEEE*

Abstract— **This paper presents a swallowable sensor device that can be ingested orally, later passing to the stomach, where the device can indwell for long periods. Using wireless communication, it can be egested at any time after it is triggered. This device can indwell using a silicone balloon in the gastrointestinal tract. A chemical reaction inflates the balloon inside the stomach. Then it is deflated to egest the sensor device using an actuator with electrolysis of water. Energy for the actuator with electrolysis can be fed wirelessly. Near field communication and a flexible antenna are used for power feeding and wireless data communication. Because of the flexible balloon and the flexible antenna, the device size can be minimized without performance degradation.**

I. Introduction

Mobile health is expected to play an increasingly prominent role in aging societies. Daily life monitoring is especially important to prevent lifestyle diseases [1]. However, it is difficult to realize a sensor device to monitor long-term internal information of the human body, including dietary habits and internal organ health. Although this information is important for lifestyle analysis, it is difficult to monitor it from outside the body [2, 3].

Implantable or ingestible devices have been developed to monitor information inside the human body [4, 5]. These devices show better usability and measurement accuracy than mobile or pasted-type sensor devices. However, psychological barriers present issues that inhibit their practical use. Therefore, this study specifically examines swallowable sensor devices for use as long-term biosignal monitors. Such sensors have less associated psychological resistance from patients than implantable devices have.

Capsule endoscopy has already come into practical medical use [6, 7]. Such capsules can transmit images from the gastrointestinal tract using wireless communication. A small lithium-ion battery and a dedicated LSI are used in such devices. Generally such devices are smaller than 15 mm × 30 mm, which is close to the swallowable limit.

A swallowable and battery-less device for drug delivery has been reported [8]. This device can transmit information related to oral medication in the stomach. This battery-less device achieves sensing by generating energy from a chemical reaction with gastric fluid.

This research was supported by JSPS KAKENHI Grant Number JP15K13913.

R. Nakamura, S. Izumi, H. Kawaguchi, and M. Yoshimoto are with the Graduate School of System Informatics, Kobe University, 1-1 Rokkodai, Nada, Kobe, Hyogo 657-8501, Japan (e-mail: shin@cs28.cs.kobe-u.ac.jp).

H. Ohta is with the Gastroenterology, Sapporo Orthopaedics and Cardiovascular Hospital, Sapporo Japan

These conventional swallowable devices are designed for short-term measurements: from several hours to 24 hr. In contrast, the device described herein is intended for long-term continuous monitoring in the gastrointestinal tract lasting from several days to several months. For indwelling of the devices into the gastrointestinal tract, a remotely controlled capsule robot with a balloon inflation function has been proposed [5]. This robot can inflate a balloon in the gastrointestinal tract using a chemical reaction of an acetic acid solution and sodium bicarbonate to produce carbon dioxide (CO_2). The gastric balloon has been used for food intake reduction during obesity treatment programs [9, 10]. Because the volume of the acetic acid solution and sodium bicarbonate is much less than the produced CO_2, the total volume of the system can be minimized while swallowing. Furthermore, the CO_2 that is produced can be evacuated. The balloon can then be deflated to egest the sensor device from the gastrointestinal tract. We used this mechanism as the indwelling method of our sensor device. Figure 1 presents an overview of the proposed system and the swallowed sensor device.

Conventional devices [5] entail the difficulty of requiring a motor to trigger both inflation using a chemical reaction and deflation by evacuation. The motor therefore occupies a certain volume in a conventional device. Furthermore, it consumes much more power than other sensor device components. That power consumption strongly constrains the device because the battery capacity is limited by the system volume. Other indwelling devices have been proposed [11, 12], but they have no on-board actuation or powering. To address these shortcomings, we proposed motor-less inflation and deflation using a chemical reaction [13].

This paper presents a small swallowable device consisting of a deflating actuator using a water electrolysis mechanism, a microcontroller unit, and a power feeding system using Near Field Communication with a flexible antenna.

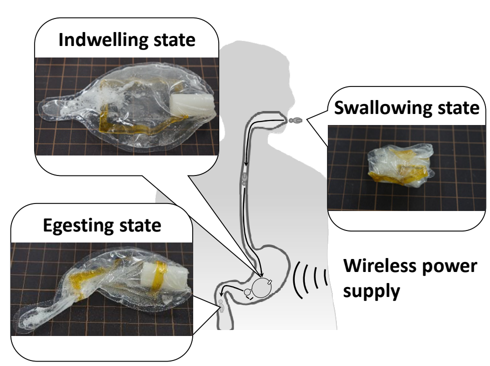

Figure 1. States of proposed swallowable device system

II. INDWELLING AND EGESTING METHODS

A. Inflation Method

To realize the easily swallowable sensor device, size reduction is a primary goal of this research. Mechanical micromotors and micropumps are commonly used as small actuators. However, their output power and energy consumption are unsuitable for our target device size. Therefore, in our previous work [13], we proposed the concept of a low-power indwelling and egestion method using a silicone balloon and a chemical reaction.

When swallowing the sensor device, the silicone balloon is divided into two portions with gelatin: an acid portion and the other portion, which includes sodium bicarbonate, as depicted in Fig. 2. Gastric juices and body temperature melt the gelatin when the device is in place in the stomach. Then, the acid and the sodium are mixed to produce CO_2 by a chemical reaction. After the reaction, the sensor is indwelled in the stomach for inflating the balloon with the generated gas, as presented in Fig. 2. This method requires no mechanical actuator or circuitry, giving the sensor device its smaller volume and low power consumption.

B. Deflation Method

The silicone balloon should be deflated by the user before egesting. To exhaust the produced CO_2, we proposed the actuator concept using electrolysis of the sodium carbonate water solution [13] because conventional actuators such as motors and pumps have high power consumption and limited miniaturizability.

Fig. 3 depicts the electrolysis actuator architecture. When electrolysis occurs by a driver circuit, a needle on a silicone film is lifted by gas produced from the sodium carbonate water solution. Then, the needle creates an exhaust hole by penetrating the balloon. The needle tip is protected by a casing even after it penetrates the balloon. The water solution and the generated gas are also covered by silicone film at all times to prevent leakage to the body.

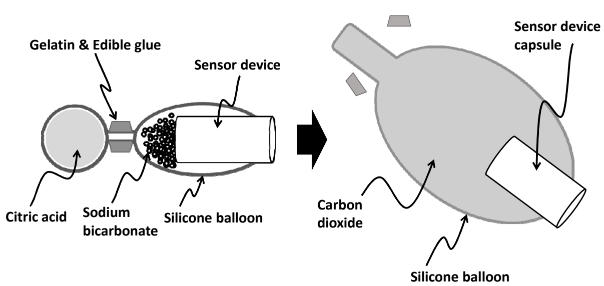

Figure 2. Inflation system of swallowable device

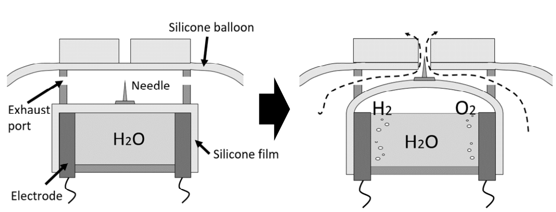

Figure 3. Architecture of proposed actuator for exhaust

III. DESIGN OF ELECTROLYSIS ACTUATOR FOR EGESTING

Herein, the authors present the overall design and implementation of the swallowable sensor device platform, which has indwelling and egesting methodologies.

First, an efficient design is regarded as realizing the evacuation actuator, the concept of which is shown in Section II. Because the actuator size is dominant in all sizes of the device even if our proposed method is adopted, it is important to optimize the efficiency.

The electrolysis efficiency, which is the key factor of our actuator, has been examined in earlier studies [14, 15]. When direct current is applied to water, the following reaction occurs. It is decomposed into hydrogen and oxygen.

$$2H_2O \rightarrow 2H_2 + O_2 \tag{1}$$

Because hydrogen ions are monovalent, 2 mol of electrons are involved in producing 1 mol of hydrogen. Accordingly, an electric quantity of 2 F is necessary to produce 1 mol of hydrogen. Here, Faraday constant F is an electric quantity of 1 mol of electron; its value is 96,485 Coulomb / mol. Because 1 m^3 of hydrogen in the standard state is 44.6 moles, the necessary quantity of electricity to generate it is 89.3 Faraday, which is 2393 Ah / Nm^3 in terms of practical units. This result indicates that 2,400-Ah charge is necessary to produce 1 m^3 of hydrogen and 0.5 m^3 of oxygen. In other words, 1.5-m^3 gas can be generated using 2,400 Ah. In our design, the required gas volume is 1.5 cm^3. The expected power dissipation is 2.4 mAh.

Fig. 4 presents the required voltages for water electrolysis [16]. The theoretical voltage to generate hydrogen and oxygen is 1.23 V at 25 °C and 1 atm. In addition, reaction overvoltage for the electrode reaction and ohmic loss is required. The ohmic loss occurs when the current flows through the electrodes and the solution. Because our target current density is sufficiently small, ohmic losses can be disregarded for the purposes of this study.

According to the analysis described above, we designed and evaluated an efficient actuator structure using water electrolysis. The power supply voltage was set to 3 V in the

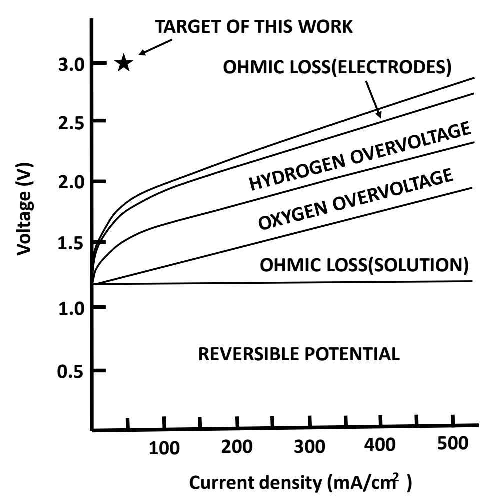

Figure 4. Relation of electrolytic voltage and current density

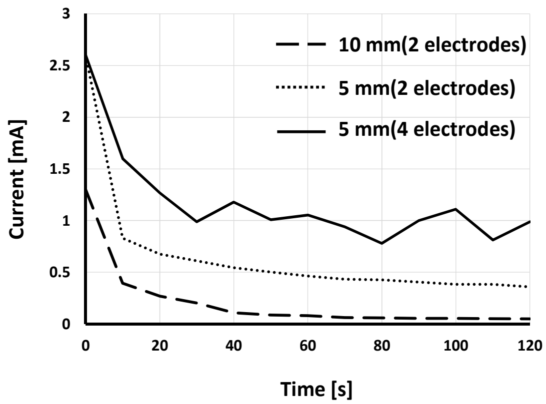

Figure 5. Relation of water electrolysis and distance of electrodes

experiment. Stainless steel screws were used as electrodes of 5 mm length and 2 mm diameter. Figure 5 presents measurement results of the current value flowing in the solution. Then, the water solution consists of 10% sodium carbonate. The experiment is conducted with three electrode placement patterns: two electrodes with 5-mm and 10-mm distances and four electrodes with 5-mm distance. The current flowing in the solution decreases with the passage of time because the bubbles generated at the surface of the electrodes increase the resistance. Results show that the number of electrodes should be increased and that the distance of electrodes should be reduced as much as possible.

According to this result, we developed the actuator structure depicted in Fig. 6. Four electrodes are placed into the water solution. Each electrode is connected to a driver circuit on a PCB. The supply voltage was set to 3 V, according to the specifications for wireless power supply (see Section IV).

IV. Design and Implementation of Sensor Device Platform with Flexible Antenna for Power Feeding

Because the battery size is strictly limited in this application, the power source is an important issue to realize long-term monitoring in the human body. The actuator, as shown in Section III, also requires a certain amount of energy.

Several energy harvesting solution candidates exist for supplying energy into the body: electromagnetic waves, ultrasound waves, and generation of electricity from biological fluids. In this work, we specifically examined wireless power feeding using near field communication (NFC). The NFC is an RFID technology that uses electromagnetic induction.

Although the dielectric constant of the human body differs from that in air, 13.56-MHz resonance frequency of NFC is sufficiently low to communicate with the swallowed device. However, a low resonance frequency requires a larger antenna. To address this problem, we designed a flexible antenna that can be combined with a silicone balloon; moreover, it can be folded for swallowing.

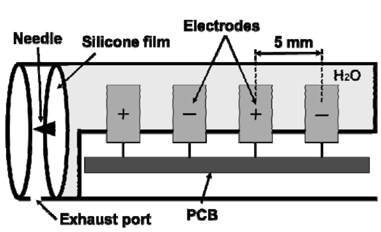

Figure 6. Proposed actuator structure

The flexible antenna is designed for creation from a standard fabrication process of a flexible printed circuit board. It has a polyimide base and two copper wiring layers. Its total thickness is 100 μm in this design. We tested the four antenna designs shown in Fig. 7 and Table 1. Each antenna is designed to have 80-pF additional capacity. Because the balloon size was 80 mm, the maximum antenna size was 60 × 40 mm^2.

Fig. 8 shows the measured communication distance in a humanoid phantom. According to this result, we chose the 60 × 40 mm^2 size antenna, which has 0.22-mm wiring width, 0.25-mm wiring interval, and three turns. The maximum communication distance is 140 mm in this implementation.

Finally, an NFC-tag IC (NT3H21) and a microcontroller (STM32L4) were implemented on a printed circuit board,

TABLE I. Parameters of Flexible Antennas

	A	B	C	D
Size [mm^2]	50×40	40×30	50×50	60×40
Wiring width [mm]	1.00	0.22	0.22	0.22
Turns	4	4	3	3

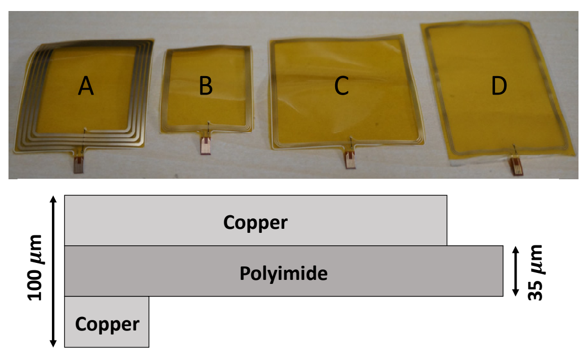

Figure 7. Flexible antennas for wireless power supply in the human body.

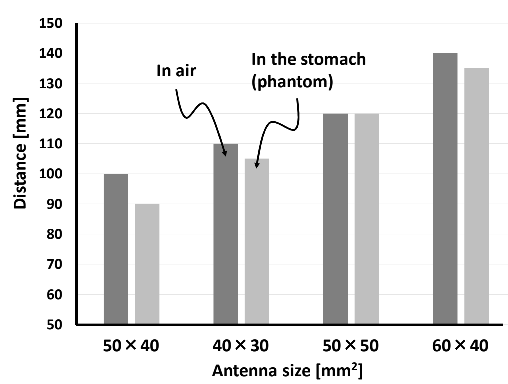

Figure 8. Maximum communication distance of antennas in the silicone balloon and humanoid phantom.

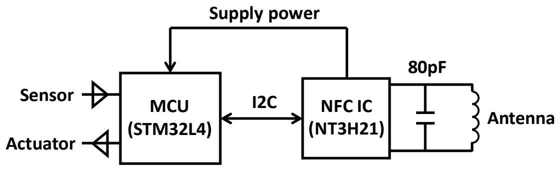

Figure 9. Circuit of sensor device

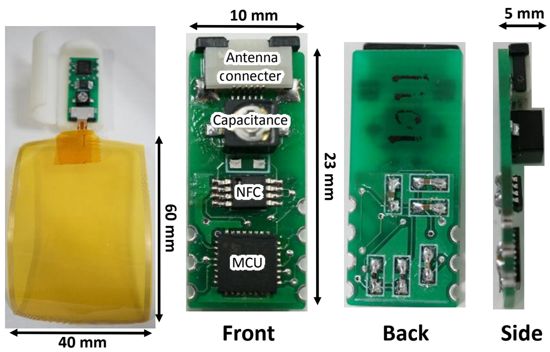

Figure 10. Flexible antenna and platform board.

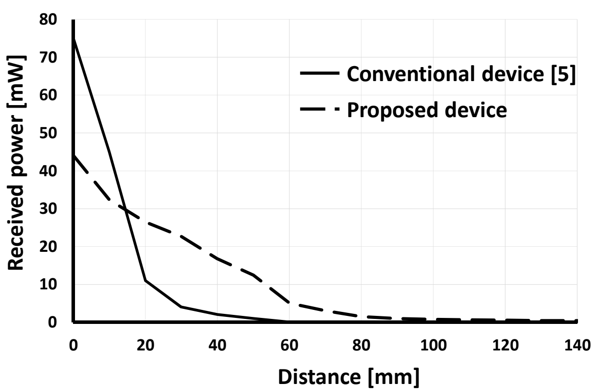

Figure 11. Comparison between a conventional device and the proposed device

which has 23 × 10 mm^2 size and 5 mm thickness, as shown in Figs. 9 and 10. The NFC-tag IC can supply 3.0 V to the microcontroller, sensors, and the actuator. Figure 11 presents a comparison of the received power with a conventional swallowable device [5] and the proposed device. For distances greater than 20 mm, the proposed device shows better efficiency. The total transmission power of this transmitter is 800 mW.

V. Conclusion

We proposed a swallowable sensor device for long-term monitoring of the gastrointestinal tract, as presented in Fig. 12. This device is useful for healthcare monitoring to observe dietary habits and internal organs. According to the chemical-reaction-based inflation method for a silicone balloon, the indwelling power can be eliminated. The proposed electrolysis actuator for evacuation and ejection can reduce the device size and power consumption.

Although the actuator power consumption is reduced, the device still has microwatt-order power consumption. This energy is expected to be supplied wirelessly from outside to inside the human body. Because the silicone balloon can also be used to compose a large flexible antenna, it is possible to realize effective wireless power feeding. In this work, NFC and flexible antennas are used to minimize the device size because it has low resonance frequency and low attenuation in the human body. Devices of our design can communicate up to 140 mm. Although a much greater communication range is necessary when the skin and fat are thick, optimization of communication circuit will be achieved in future work.

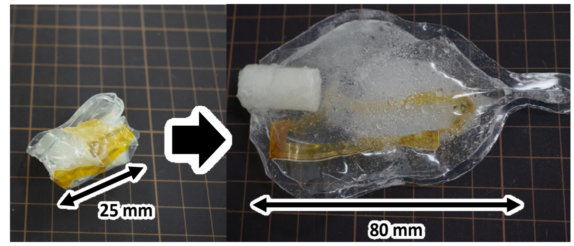

Figure 12. Proposed swallowable sensor device.

References

[1] M. Kudo, "Robot-Assisted Healthcare Support for an Aging Society," in *the Annual SRII Global Conference* (SRII), pp. 258-266, 2012.

[2] Q. Huang, W. Wang, and Q. Zhang, "Your Glasses Know Your Diet: Dietary Monitoring using Electromyography Sensors," in *IEEE Internet of Things Journal*, vol. PP, no. 99, pp. 1-1

[3] M. A. T. Turan and E. Erzin, "Food intake classification using throat microphone," *2016 24th Signal Processing and Communication Application Conference (SIU)*, Zonguldak, 2016, pp. 1873-1876.

[4] Enver G. Kilinc, Mehrdad A. Ghanad and Franco Maloberti, "A Remotely Powered Implantable Biomedical System with Location Detector," *IEEE Trans. BioCAS*, vol. 9, no. 1, pp. 113–123, Feb. 2015.

[5] Liang Yan, "Capsule Robot for Obesity Treatment with Wireless Powering and Communication," *IEEE Trans. Industrial Electronics*, vol. 62, no. 2, February 2015.

[6] D. K. Iakovidis, E. Spyrou, D. Diamantis, and I. Tsiompanidis, "Capsule Endoscope Localization based on Visual Features," *in Proc. of IEEE, BIBE*, pp. 1-4, November. 2013.

[7] Fei Xu, Guozheng Yan, Li Lu, Jinyang Gao, and Gang Liu, "A Wireless Capsule System With ASIC for Monitoring the Physiological Signals of the Human Gastrointestinal Tract," *IEEE Transl. on Biomedical Circuits and Systems*, vol. 8, no. 6, pp. 871–880, Dec. 2014.

[8] Stephen P. Woods and Timothy G. Constandinou, "Wireless Capsule Endoscope for Targeted Drug Delivery," *IEEE Trans. Biomedical Engineering*, vol. 60, no. 4, pp. 945–953, April 2013.

[9] O. G. Nieben and H. Harboe, "Intragastric balloon as an artificial bezoar for treatment of obesity," *Lancet*, vol. 319, no. 8265, pp. 198–199, January 1982.

[10] J. –M. Dumonceau, "Evidence-based review of the BioEnterics Intragastric Balloon for weight loss," *Obesity Surg.*, vol. 18, no. 12, pp. 1611–1617, Dec. 2008.

[11] S. Yim and Metin Sitti, "Shape-programmable soft capsule robots for semi-implantable drug delivery," *IEEE Transactions on Robotics*, vol. 28, no. 5, 1198-1202, 2012.

[12] Do, Thanh Nho, Khek Yu Ho, and Soo Jay Phee. "A Magnetic Soft Endoscopic Capsule-Inflated Intragastric Balloon for Weight Management," *Scientific Reports* vol. 6, 2016.

[13] R. Nakamura et al., "Swallowable Sensing Device for Long-term Gastrointestinal Tract Monitoring," *Proc. of IEEE EMBC*, pp. 3039–3042, Aug. 2016.

[14] R. L. LeRoy, "Industrial water electrolysis: Present and future," *Int. J. Hydrogen Energy*, vol. 8, no. 6, pp. 401–417, 1983.

[15] T. Iida et al., "Water Electrolysis under a Magnetic Field," *Journal of the Electrochemical Society*, vol. 154, no. 8, pp. E112–115, 2007.

[16] R. L. LeRoy et al., "Analysis of Time-Variation Effects in Water Electrolyzers," *J. Electrochem. Soc., Electrochemical Science and Technology*, vol. 126, no. 10, pp. 1674–1682, Oct. 1979.