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Liquid-Based Digital Readable Tilt Sensor

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It is crucial for tilt sensors to be driven by simple systems for motion-tracking devices, robot control, and aviation equipment. However, in current tilt sensors, measurement error accumulation, which is known as drift, occurs owing to complicated calculations. Moreover, to mitigate drift, an alternating current or optical equipment is required, which increases the complexity of the observation system. Thus, for further application of tilt sensors, a simple measurement system is essential. In this study, a sensor that can detect tilt by simply turning a direct current on and off using a conductive liquid material is developed. This sensor detects the direction and angle of the tilt in two dimensions, and it does not require an external calculation mechanism because it detects the tilt directly as a digital signal. A leveling machine with thermal actuators and a wearable device is demonstrated as applications of the developed sensor. This sensor realizes angle detection with a simple mechanism and structural solution, which is significant in the field of wearable devices and robots.

1. Introduction

Tilt sensors, which are among the most important physical sensors, are used in aircraft altitude estimation[1–4], drone attitude control,[5–8] and human motion tracking.[9–12] In general, an inclination-sensing device using micro-electromechanical system (MEMS) technology consists of acceleration and angular rate sensors.[13,14] It detects the angular velocity by determining the Coriolis force on the vibrating body and calculates the inclination angle by integrating the obtained data. However, the large error caused by drift accumulation is a serious problem, the solution to which requires complex systems and cumbersome programs.

To solve these problems, inclination sensors that can measure the tilt angle directly have been developed. Direct inclination sensors are larger than MEMS gyroscopes. Furthermore, it is possible to obtain the tilt state electrically by using liquid,[15–22] a metal ball and springs,[23] a pendulum,[24,25] or metal microspheres.[26] Among these, inclination sensors that consist of liquid material can detect the direction and angle simultaneously. Compared to solid materials, liquid materials offer the advantages of high resolution, stability, and the ability to detect both the angle and direction. Electrolytes,[15,16,22] liquid metals,[17] and magnetic fluids[18,19] are mainly used as sensing materials.

However, the commonly used tilt sensors generally detect the tilt angle based on the contact area between the electrolyte and electrode. It is possible to detect the angle as a continuous value by acquiring the tilt using such a method. Moreover, detection by an alternating current (AC) is essential because the electrolyte does not conduct direct current (DC). The electrical processing of AC is more complicated than that of DC. Thus, tilt sensors composed of liquid materials have complicated external circuits for AC generation and analysis.

Therefore, research has been conducted on tilt sensors using liquid metal as a DC conductive liquid material.[17] As liquid metal has a very high electrical conductivity, tilt can be easily detected using only the information about DC conduction and insulation. Furthermore, liquid metals have extremely high surface tensions and form oxide films on their surfaces,[27–29] which makes them less liquid than other common fluids. A droplet of the liquid metal inside the tilt sensor results in slight deformation/flow. Therefore, although the tilt direction can be detected, it is difficult to determine the actual tilt angle.

This article proposes a digital readable tilt sensor using a conductive liquid material. As this sensor uses a conductive liquid, the tilt can be detected based on the digital reading (i.e., the electrical on–off signal) of the DC alone and it is not necessary to generate or use AC. In addition, the sensor can detect not only the tilt direction, but also the actual tilt angle, because the conductive liquid developed in this study has greater liquidity than liquid metal.

2. Device Architecture and Fabrication Scheme

Figure 1 presents a schematic of the sensor, which consists of a liquid-filled shell and substrate. A conductive dispersion of carbon nanotubes (CNTs) inside the shell is used as the sensing material (Figure 1a). The liquid provides conductivity according to the inclination direction, and the inclination can be obtained from an electrical on–off signal (Figure 1b). As the

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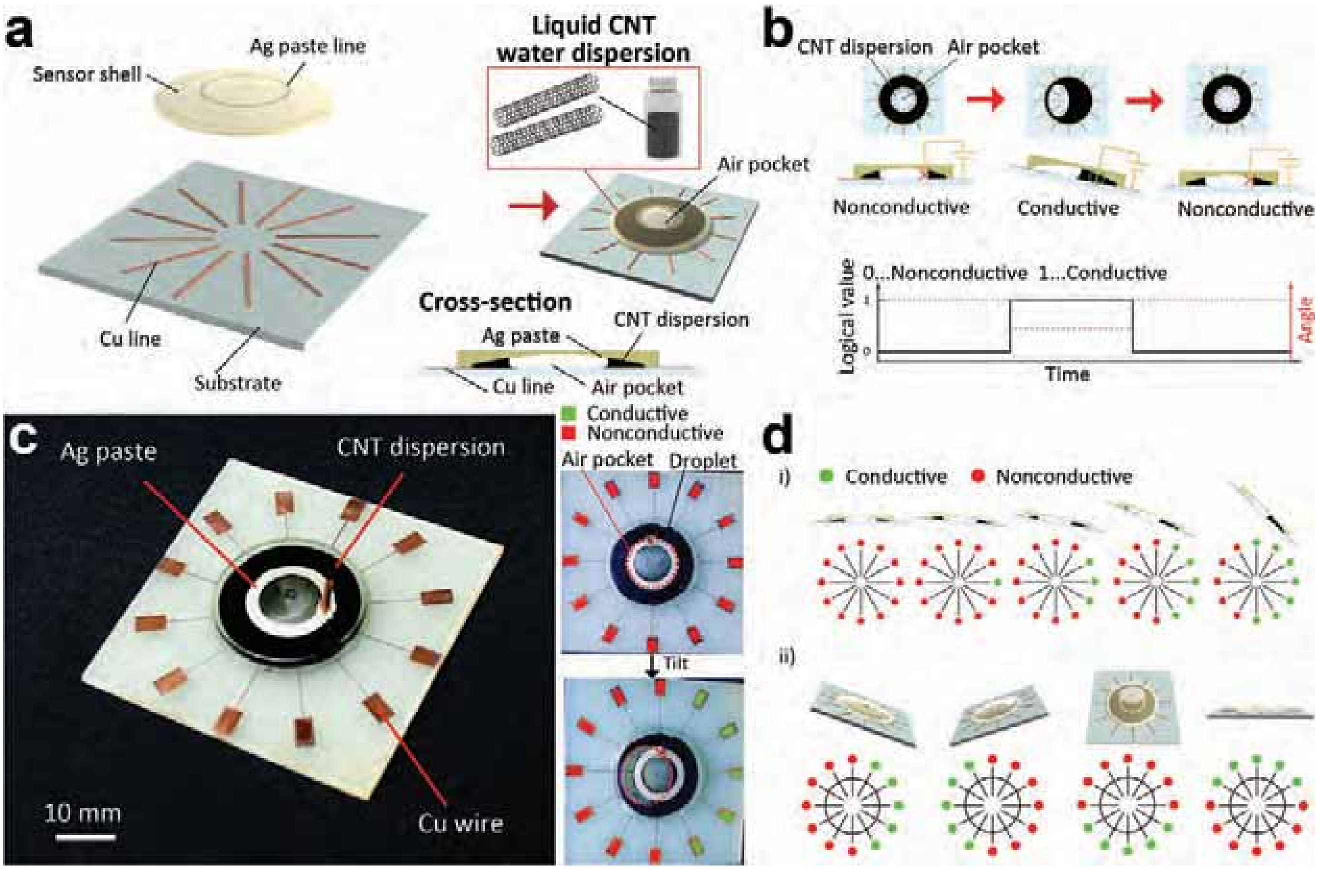

Figure 1. Concept of the digital readable tilt sensor using conductive liquid. a) Device consisting of a shell and circuit board. The shell contains conductive liquid in which CNTs are dispersed. b) Measurement mechanism. The sensor detects the tilt using a binary DC on–off signal using the CNT dispersion as the sensor element. c) Photograph of the fabricated device. When an inclination is applied, an air pocket flows inside the liquid and the electrode that is in contact with the liquid changes. d) Detection of the tilt angle and direction. The sensor can detect both the tilt angle in one direction and 12 tilt directions: i) one-direction tilt angle measurement; ii) 12-axis direction measurement.

conductive liquid CNT dispersion is more fluid than the liquid metal, the liquid flows freely according to the inclination. In the tilted state, the "air pocket" moves to switch the conduction and insulation of the electrodes (Figure 1c). This feature offers the advantage that the inclination direction can be detected without any external calculation mechanism. Furthermore, owing to the high fluidity of the liquid material, in addition to the inclination direction, the inclination angle in one direction can be measured in the device (Figure 1d).

The liquid material inside the sensor and the shell structure are the two main factors that determine the device performance. When the sensor is tilted, as shown in Figure S1 in the Supporting Information, the liquid is subjected to gravity (F_g), resistance due to viscosity (F_v), and attraction due to wettability (F_γ) from the shell wall. The resistance due to viscosity decreases when the viscosity is lower, and the attraction due to wettability increases downward when the wettability is higher. When the wettability is poor and the contact angle is greater than $\pi/2$, the liquid experiences an upward drag force from the wall. Moreover, these combined forces increase downward when the space inside the shell is large. Therefore, the wettability, viscosity, and size of the space inside the shell affect the flowability of the fluid.

To construct the device, we first selected the liquid material to serve as the sensing element. We ensured conductivity by dispersing the CNTs in common polar solvents, namely, isopropyl alcohol (IPA) (2-propanol), *N*-methylpyrrolidone (NMP), and water. IPA has high wettability, and NMP has excellent dispersibility. However, as illustrated in Figure S2 (Supporting Information), these solvents have high viscosities and are unsuitable for flowing in a narrow shell. Therefore, water was selected as the solvent.

Takei et al.[17] proposed a tilt sensor using liquid metal as a conductive liquid material. In the present study, only the tilt direction was determined by detecting the minute movement of the liquid metal. However, as indicated in **Figure 2a**, the liquid metal had quite a large sliding angle and surface tension, which made it difficult to generate an air pocket for the tilt detection (Figure S3, Supporting Information). In terms of tilt sensing using the liquid metal droplet, to keep the droplet on the substrate based via surface tension, the droplet size had to be small, which limited the number of electrodes. Consequently, the resolution of the tilt direction decreased. Because the liquid used in this study can be driven on the order of milliliters, the sensor size and number of wires can be arbitrarily changed according to the application.

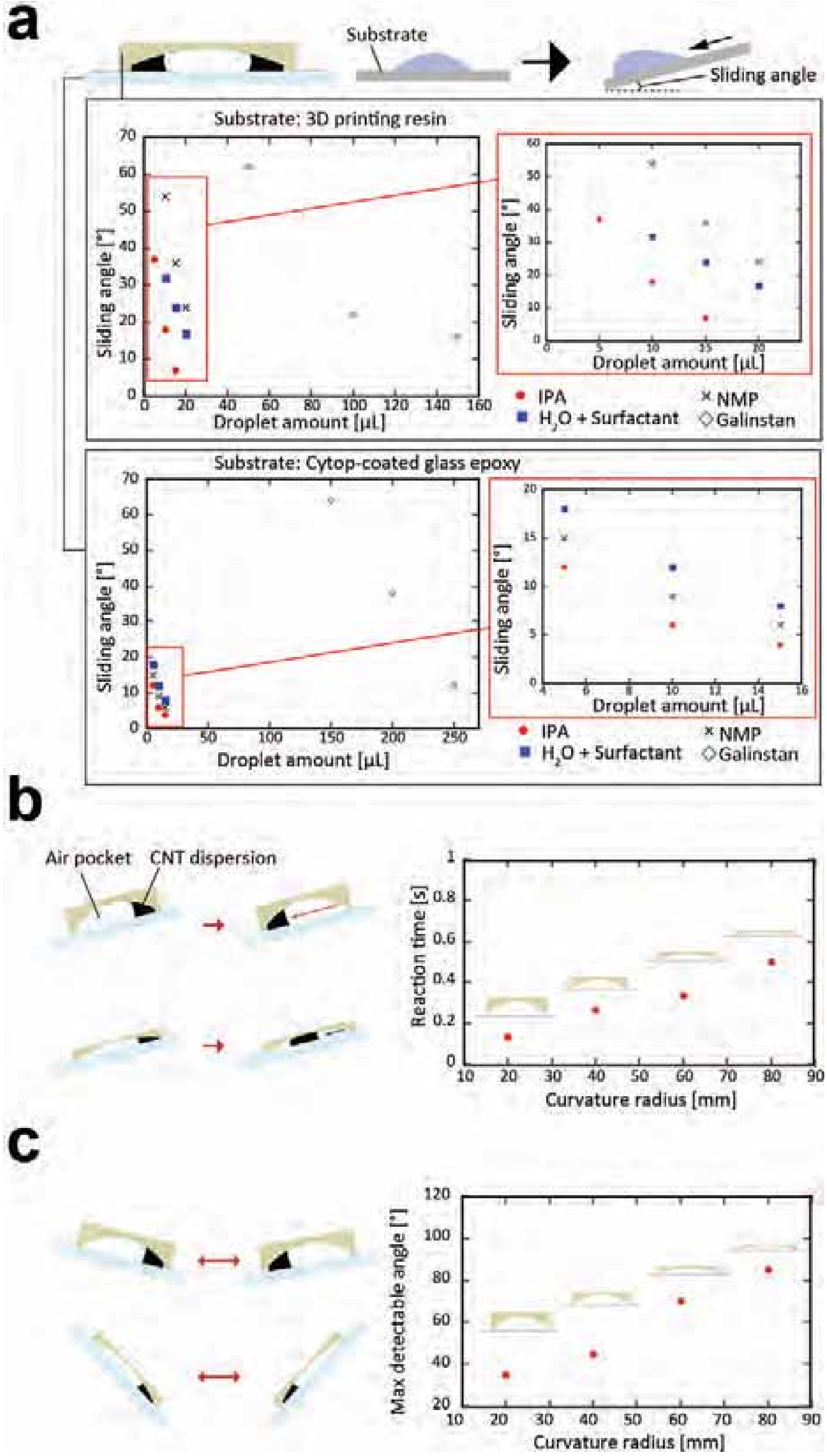

Figure 2. Material and structure design considerations for the tilt sensor using conductive liquid materials. a) Sliding angle of the liquid. The liquid metal has a large sliding angle owing to the oxide film on the surface, making it difficult to use in this sensor as it requires high flowability. The other three polar solvents all have low sliding angles. b) Reaction rate variation with the shell arc curvature radius. When the curvature radius is smaller, the space inside the shell is wider and less time is required for the liquid to slide down after tilting. c) Measurable range variation with the shell arc curvature radius. When the curvature radius is larger, the space inside the shell becomes smaller. As wetting of the liquid occurs owing to the formation of a meniscus, larger inclination is required for the liquid to slide down, resulting in a larger measurable range.

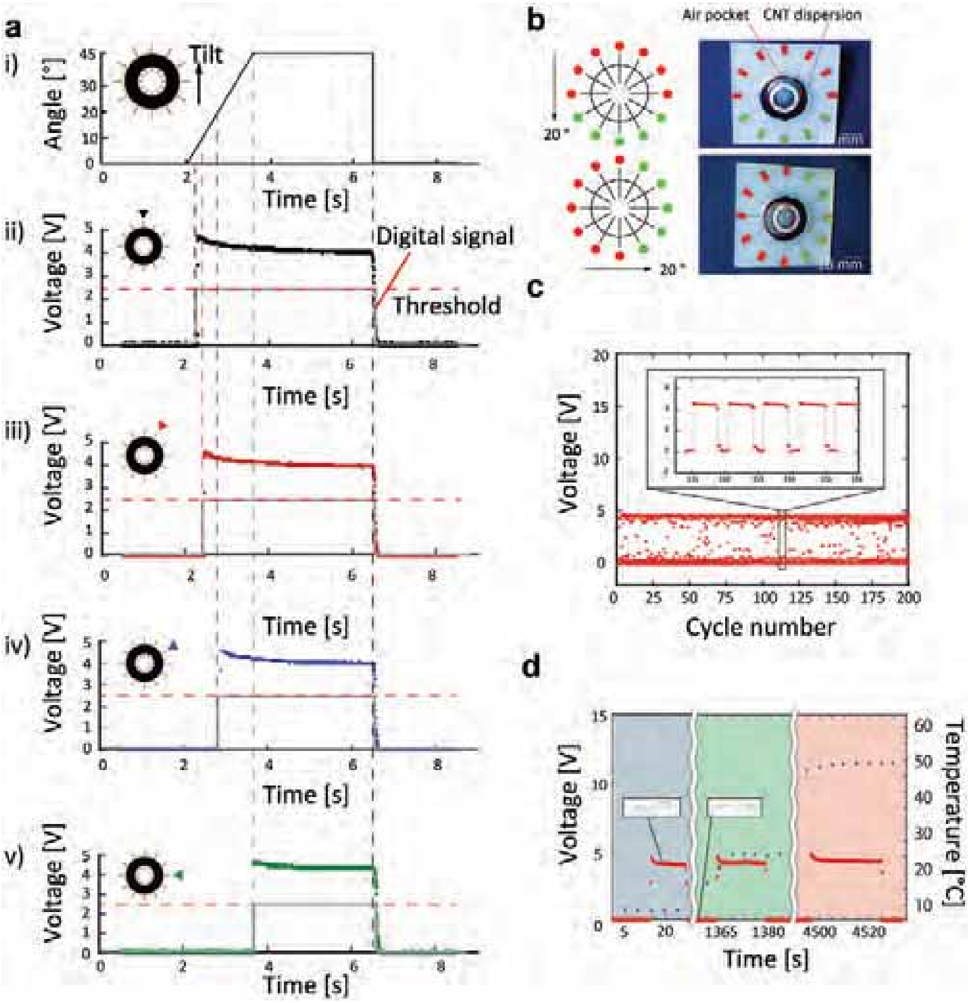

Figure 3. Electrical characteristics of developed sensor under tilting conditions. a) Conduction of each electrode during unidirectional tilting. The number of conduction electrodes increases with increasing tilt angle. b) Tilt direction detection. The conducting electrodes when the same tilt angle was applied in different directions are illustrated. c) Repetition tolerance. We performed 200 cycles of tilt tests and measured the voltage that was applied to the electrodes in the tilt direction. d) Temperature independence test results. We performed the same tilt test at three different temperatures and measured the voltage applied to the electrode in the tilt direction. There was no change in the voltage with the temperature, indicating that the system was independent of the external environment temperature.

Second, we investigated the structure of the sensor body. The upper part of the inner surface of the sensor shell had an arc shape, making it possible for the air pocket to remain in a specific place under a certain slope (Figure S4, Supporting Information). Moreover, Choi et al.[16] reported that the arc shape of the upper surface improves the recovery speed when the surface returns to the horizontal direction. Therefore, the curvature radius of this arc is an important parameter describing the shell shape.

As illustrated in Figure 2b, when the curvature radius of the shell is small, the fluid becomes more fluid because the space in the fluid flow region becomes larger, which increases the reaction speed. However, as illustrated in Figure S5 in the Supporting Information, when the space inside the shell is narrow, significant wetting of the liquid wall owing to meniscus formation occurs, which reduces the flowability of the liquid but increases the maximum detectable angle, as indicated in Figure 2c. The reaction rate and measurement range can be adjusted by changing the curvature radius of the shell arc, and the desired characteristics can be obtained according to the intended purpose.

3. Tilt-Sensing Characteristics

Figure 3a depicts the potential change in each electrode when the sensor was tilted in one direction. We applied a voltage of 5 V to the top of the sensor and measured the potential on the bottom electrode (Figure S6, Supporting Information). As can be observed from Figure 3a, the number of conducting electrodes increases with increasing tilt angle. The tilt angle measurement error was ≈15%, and the resolution had four levels: 5°, 8°, 20°, and >45°, where the resolution increased as the number of wires increased up to 12 electrodes (Figure S7, Supporting Information). However, regarding the design and material selected for use in the sensor shell, the resolution did not change when the number of wires exceeded 12, owing to the wettability of the liquid and the sensor size. If the distance between adjacent wires is too small, the individual electrodes cannot detect conductivity independently. To solve this problem, sensor size, wiring position, and material selection optimization was crucial. The digital leaded tilt sensor proposed by Takei et al.[17] has all the wiring for tilt detection laid on the substrate at the bottom of the sensor. Thus, this sensor requires two electrodes, one positive and one negative, per direction, which limits the number of detectable directions. In the present study, the electrodes corresponding to the cathode were laid on the back of the upper shell; thus, one electrode on the bottom was sufficient for each direction. The resolution was high in the shallow tilt region but decreased with respect to the tilt angle, as the wiring was laid out in a circular arrangement of electrodes. Devices using electrolytes and AC that could detect 1° inclination and 360° measurements have been reported in previous studies. These devices were composed of a Wheatstone bridge circuit and a function generator for AC generation. Only two axes were measured, and the tilt direction was calculated numerically from these values. The device fabricated in the present study offers the advantage of simplicity in that it can perform measurement using only a single DC power supply, such as a coin battery, and that both the tilt direction and angle can be determined directly without any complicated calculations.

Figure 3b presents the results of the direction detection test. The conduction between the electrodes was detected when the inclination was 20° to the rear and to the right. As illustrated in Figure 3b, the pocket inside the shell moved according to the inclination direction and the position of the conduction electrodes changed accordingly to detect the inclination direction. Direction detection in 12 directions was possible because the sensor fabricated in this study had 12 wires. Büthe et al.[26] proposed the use of micrometal spheres to fabricate a digital reed tilt sensor using conductive materials. In contrast to the aforementioned liquid metal sensor, this sensor could measure inclination angles up to 360°. However, it could not detect the inclination direction and the sensor plane had to be tilted by more than 50° from the horizontal direction to achieve sufficient performance. In the present study, the proposed sensor could detect not only the tilt angle, but also the tilt direction. The results of the repeatability test with 200 trials, depicted in in Figure 3c, demonstrate that the sensor provides excellent repeatability. In addition, as this sensor uses water dispersion as the sensor material, the amount of sensor material decreases as the water evaporates. The outer shell and bottom substrate of the sensor used in this study are composed of acrylic resin and glass epoxy resin, both of which have low gas permeability. Therefore, the evaporation of water is considered to occur through a small gap in the elastic epoxy resin that seals the interface between the sensor outer shell and the glass epoxy resin. This gap is very small; thus, the sensor can be used for more than two weeks. In the future, it will be possible to use ionic liquids that do not have vapor pressure as dispersants, which will solve the problems associated with solvent volatilization.

We performed a single-axis tilt test by using the developed sensor under various ambient temperature conditions. We placed the system in a thermostatic bath and conducted the inclination test under different temperature conditions. As illustrated in Figure 3d, we conducted the tilt test in three different temperature ranges and the signal transfer at each temperature is similar. A temperature-independent tilt sensor using a solid material was reported previously.[30] The sensor had a measurement error of ≈0.4° in the temperature range of 27–65 °C and a high resolution of 0.83°. However, the observation system was very complicated because an optical system was used for measurement and the 2D inclination direction could not be detected. The device fabricated in this study was structurally designed to suppress the angle measurement error owing to temperature, which eliminated the need for calibration calculations. Moreover, it offers the advantage of simplifying the system for applications, including wearables and robotics, because it enables easy electrical detection of the angle and direction.

As water was used as the liquid of the sensor developed in this study, there is a possibility of freezing at temperatures below 0 °C. This problem can be solved by adding antifreeze or changing the material. Moreover, the heat-resistant temperature of the resin used in the 3D printer to fabricate the sensor is ≈60 °C, making it difficult for the current device to perform measurements at higher temperatures.

4. Tilt Sensor Applications

4.1. Thermally Driven Parallelism Actuator Demonstration

A thermally driven parallelism actuator using the tilt sensor was developed as an application thereof (**Figure 4**a; Video S1, Supporting Information). Figure 4b presents the circuit diagram of each “leg.” The actuator consisted of a sensor, an N-channel MOSFET, and a heater. The current passing through the sensor opened and closed the transistor gate to regulate the power supply to the heater. Figure 4c depicts the relationship between the voltage applied to the heater and the temperature of the heater, which was increased to more than 40 °C with a voltage supply of ≈1 V.

Figure 4d shows the operating mechanism of the actuator and the driving test results. The transistor opened or closed the gate by detecting the tilt with the sensor, which supplied power to the heater to boil the low-boiling-point solution and returned to the horizontal position. When the actuator was horizontal, no conductive liquid contacted the electrodes inside the sensor. The current that was supplied from the top did not flow into the transistor (Figure 4d (i)). Consequently, the transistor did not pass a current and no power was supplied to the heater. As illustrated in Figure 4d (ii), when the system was tilted, the liquid inside the sensor flowed and contacted the electrodes. This behavior caused the current that was supplied from the top to increase the transistor gate potential, and the drain and source were opened to supply electrical power to the heater. The balloon placed on the underside of the heater was heated and filled with the low-boiling-point liquid. This process caused the liquid to boil and the balloons to expand, thereby lifting the tilted legs. The balloon returned to the horizontal state and the current to the transistor gate was cut off again (Figure 4d (iii)). The heater, which lost its power supply, was gradually cooled

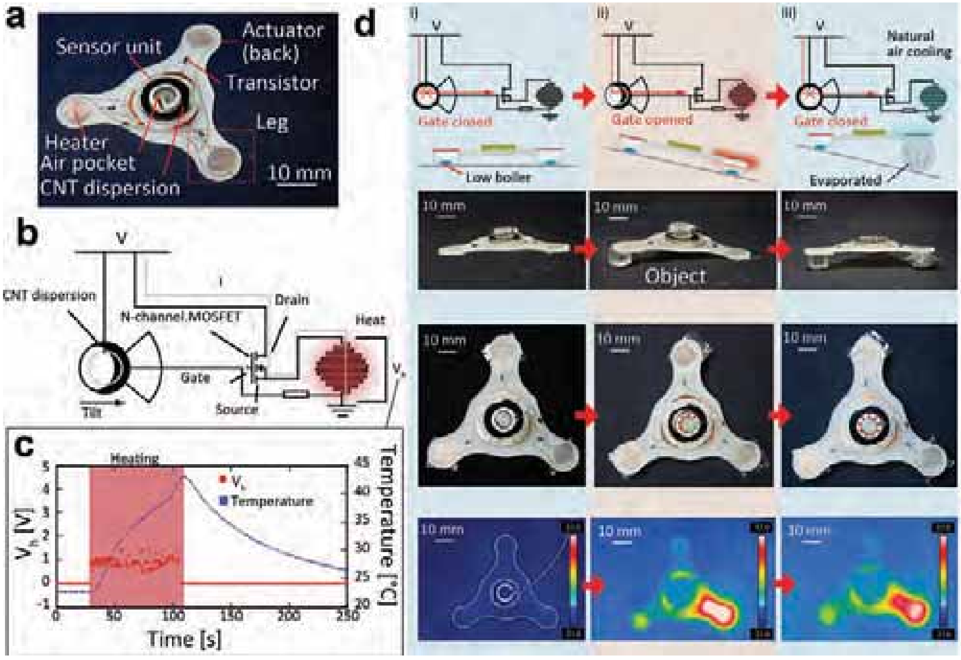

Figure 4. Demonstration of thermally driven parallelism actuator. a) Photograph of fabricated actuator. b) Circuit on top of actuator. The gate electrode of the MOSFET was connected to the sensor and the gate was opened when the sensor was conducted by the tilt. c) Correlation between voltage over heater and heater temperature. The heater temperature reached 34 °C, which was the boiling point of the liquid, within ≈20 s after the voltage was applied. It reached over 40 °C within ≈70 s. d) Mechanism of tilt detection and horizontal recovery. When the device was tilted, the transistor gate opened and current was applied to the heater. This caused the liquid inside the balloon to boil and the device returned to the horizontal direction. The heater started to air cool naturally when the voltage from the sensor was cut off after the device became horizontal.

by air cooling. This operation was repeated according to the tilt direction to maintain the horizontal position of the actuator.

The low-boiling-point liquid used in this actuator, NOVEC7000, has a boiling point of 34 °C. The balloon mechanism has been used to drive soft actuators previously, but these actuators require an external air pump. The driving speed of this device is not as fast as that of a pneumatic actuator, and it takes about 1 min to return to the horizontal from the tilted state. This behavior occurs because it takes time to boil a liquid to a gas by heating. In addition, once the thermal actuator has expanded, it returns to its initial state when the boiled gas returns to the liquid state, so it is necessary to wait for natural cooling in this device, which does not have a cooling mechanism. In this device, the time required for the actuator to return to the inclined state after expanding to the horizontal level was about 5 min at an outdoor temperature of 25 °C. This time can be reduced by changing the device material to improve the waste heat efficiency and by installing a cooling mechanism. In addition, this device offers the advantage of simplicity because the total system is driven by a single power source. In addition, this device can be applied to small actuators that cannot be equipped with complex systems because this actuator does not require a control mechanism and can be driven only by a single power supply. Further, because the system is simple, it is difficult to cause malfunctions, so it is considered to have excellent long-term durability and is suitable for long-term application to process that occur on a weekly scale, such as plant growth and the melting and resolidification of ice.

4.2. Head Motion Tracking Device Demonstration

A device that could track head-turning was developed as an additional application using the sensor (**Figure 5**a; Video S2, Supporting Information). Figure 5b presents the operation principle. This device consisted of a sensing unit, a microcontroller unit (MCU) for data analysis, a Bluetooth low-energy (BLE) module for transmission, a coin cell battery to drive these components, and a power regulator. Once all the signals from the 12 electrodes had been measured, the BLE module sent the 12-digit signal to the computer. Figure 5c depicts the results of the unidirectional tilt test. The number of electrodes that were connected via the conductive liquid increased incrementally with the movement of the head. In this sensor, four levels of angles could be detected: 0°–8°, 8°–20°, 20°–45°, and >45°. Figure 5d presents the results of the direction detection using the sensor, which indicates the detection of the current inclination of the head with 360° free rotation. The inclination angle was set to 45° in all directions because the tilt limit of the human neck is ≈50°–60°, and the sensor could detect the orientation of the head in 12 steps. This device could read not only the tilt in one direction, but also the angle.

When considering the installation of the sensor in locations other than the head, the measurement range and resolution should be changed according to the purpose. A tilt sensor using liquid metal devised by Takei et al.[17] was used for posture estimation by implementation as a wearable device for infants. This device can monitor infants and prevent dangerous postures,

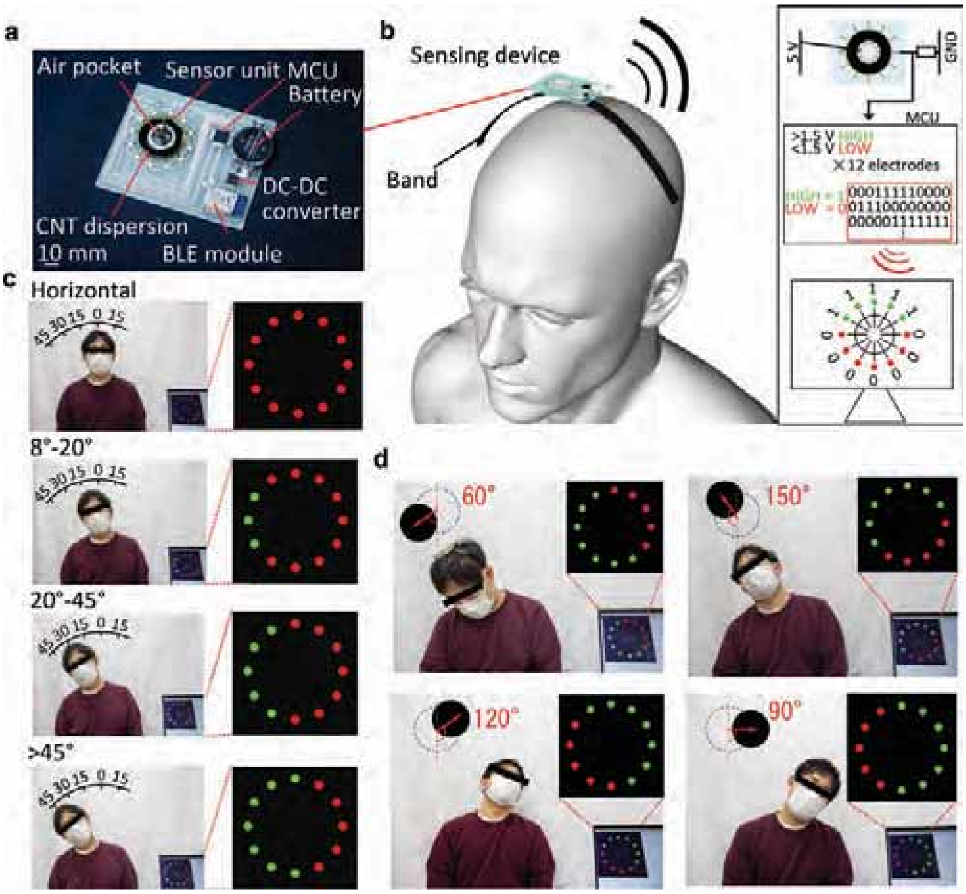

Figure 5. Head-turning tracking demonstration. a) Photograph of the device. b) Operation overview. The device was equipped with an MCU and a BLE module, which converted the acquired conduction data in 12 directions into 12-digit binary numbers and transmitted them to a computer wirelessly. c) Unidirectional tilt test. When the head was inclined in the same direction, the number of conduction electrodes increased with the head inclination. d) Tilt direction measurement test. When the head was inclined in different directions, the conduction electrodes showed the orientation according to the tilt direction.

such as prone positions, during sleep, but it could affect respiration when adhered directly to the body. Therefore, the inclination angle was not measured, but the inclination direction was detected. In this research, the tilt sensing device was designed to detect both the tilt direction and angle because it was applied to the head, which can tilt freely in all directions and at all angles.

5. Conclusion

In this study, we developed a digital readable tilt sensor using a conductive liquid material. The sensor measures the tilt angle based on the binary information of the conductivity and insulation of the conductive liquid. It can obtain the 2D information of the tilt direction and angle without an external computing mechanism. The resolution is 0°–8°, 8°–20°, 20°–45°, and >45° in a single direction, and 12 steps in the inclined direction. The response speed and measurable range can be adjusted by changing the structure of the sensor, and any characteristic can be obtained. Because this research achieved tilt measurement with a simple system, it can be applied to the fabrication of small sensors, including processing systems. This system is expected to be implemented in wearable devices that do not interfere with daily life and robots in which it is difficult to install large equipment in the future.

6. Experimental Section

Material Preparation: The conductive liquid used in this sensor was a mixture of Tuball Coat_E (Kusumoto Chemicals) and BYK-051 (BYK) as a defoaming agent (3% by volume). Tuball Coat E is a mixture of a water-soluble medium and sodium dodecylbenzenesulfonate 1 wt% as a surfactant, in which 0.1–0.4 wt% of single-walled CNTs were dispersed.

Device Fabrication: Figure S8 in the Supporting Information depicts the device fabrication method. The sensor was composed of an upper shell and a lower substrate. First, the upper shell was fabricated using a 3D printer (i). Second, a circular mask of polyimide tape was attached to the shell and conductive silver paste was applied to create circular wiring inside the shell (ii). The shell was completed by peeling off the mask (iii). Third, the lower part of the substrate was fabricated. A glass epoxy substrate coated with photoresist on top of the thin copper film plating was prepared and exposed to the wiring shape using a photomask (iv). After developing and cleaning the unnecessary resist (v), the copper plating was patterned with wet etching (vi). Thereafter, Cytop 809M

(AGC Chemicals), which is a strong water-repellent and insulating material, was spin-coated onto the top surface at 500 rpm for 20 s to cover the copper pattern (vi). The coated Cytop film was laser-irradiated to create contact areas (vii) and finally was bonded to the fabricated shell using a resilient epoxy resin (viii).

One-Direction Signal Detection: Figure S6 in the Supporting Information presents the tilt test method in one direction. A voltage of 5 V was applied to the circular wiring inside the shell, and the lower wiring was connected to the GND through a fixed resistor of 10 MΩ. The potential of the lower wiring of the sensor was measured using an oscilloscope.

Actuator Fabrication: Figure S9 in the Supporting Information depicts the thermal actuator fabrication method. The actuator consisted of three parts: a sensor unit, sensor wiring, and actuator wiring. First, the sensor shell was fabricated using a 3D printer (i), following which circular wiring was laid by applying conductive silver paste after masking with polyimide tape (ii). The sensor shell was completed by peeling off the polyimide tape (iii). Second, the wiring of the lower part of the sensor was fabricated. The copper-plated and resist-coated glass epoxy substrate was cut into a disk shape and exposed using a mask (iv). After the unnecessary resist had been removed (v), the copper wires were patterned with wet etching (vi). Cytop 809M was spin-coated onto the substrate at 500 rpm for 20 s (vii), and the conductive part was exposed by laser irradiation (viii). The sensor shell was attached using a resilient epoxy resin (ix), and the sensor unit was produced. Finally, the actuator wiring, including the heater, was fabricated.

After that, copper plating and resist coating on the glass epoxy substrate were cut out by a numerical control (NC) milling machine and exposed using a photomask to fabricate a wiring pattern (x). Following development and etching (xi), a circular depression was cut into the center using the NC milling machine (xii), and transistors and fixed resistors were laid onto the substrate (xiii). The sensor unit was placed in the central depression and connected to the actuator wiring using silver paste (xiv), and finally, a plastic bag balloon was attached to the back of the actuator (xv).

Head Movement Tracking Device Fabrication: Figure S10 in the Supporting Information presents the head-turning tracking device fabrication method. The device consisted of a sensor unit and a circuit part. First, the sensor shell was fabricated using a 3D printer (i), masked with polyimide tape, and subsequently coated with conductive silver paste (ii). Once the polyimide tape had been peeled off, the sensor shell was complete (iii). Second, a substrate for the lower part of the sensor unit was fabricated. A glass epoxy plate coated with copper film and resist was cut into a circular shape by NC milling and exposed using a photomask (iv). Following development (v), the copper film was patterned with wet etching (vi). Cytop 809M was spin-coated onto the top surface at 500 rpm for 20 s (vii), and the electrical contact area was exposed by laser irradiation (viii). Finally, the sensor shell was attached, and the sensor unit was produced (ix).

Third, a circuit board was fabricated. A glass epoxy plate coated with copper film and resist was exposed using a photomask (x), developed (xi), and etched (xii). An indentation for the sensor unit was created using an end mill, and integrated circuits were laid in the indentation (xiii). Finally, the sensor unit was connected to the circuit with conductive silver paste and the device was completed (xiv). Figure S11 in the Supporting Information presents a circuit diagram of this device.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

carbon nanotube, conductive liquid, tilt sensor

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ADVANCED MATERIALS TECHNOLOGIES

Supporting Information

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Liquid-Based Digital Readable Tilt Sensor

*Ryosuke Matsuda, Song Zihao, Umihiro Kamoto, and Hiroki Ota**

Supporting Information

Liquid-Based Digital Readable Tilt Sensor

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Theoretical value of force applied to fluid

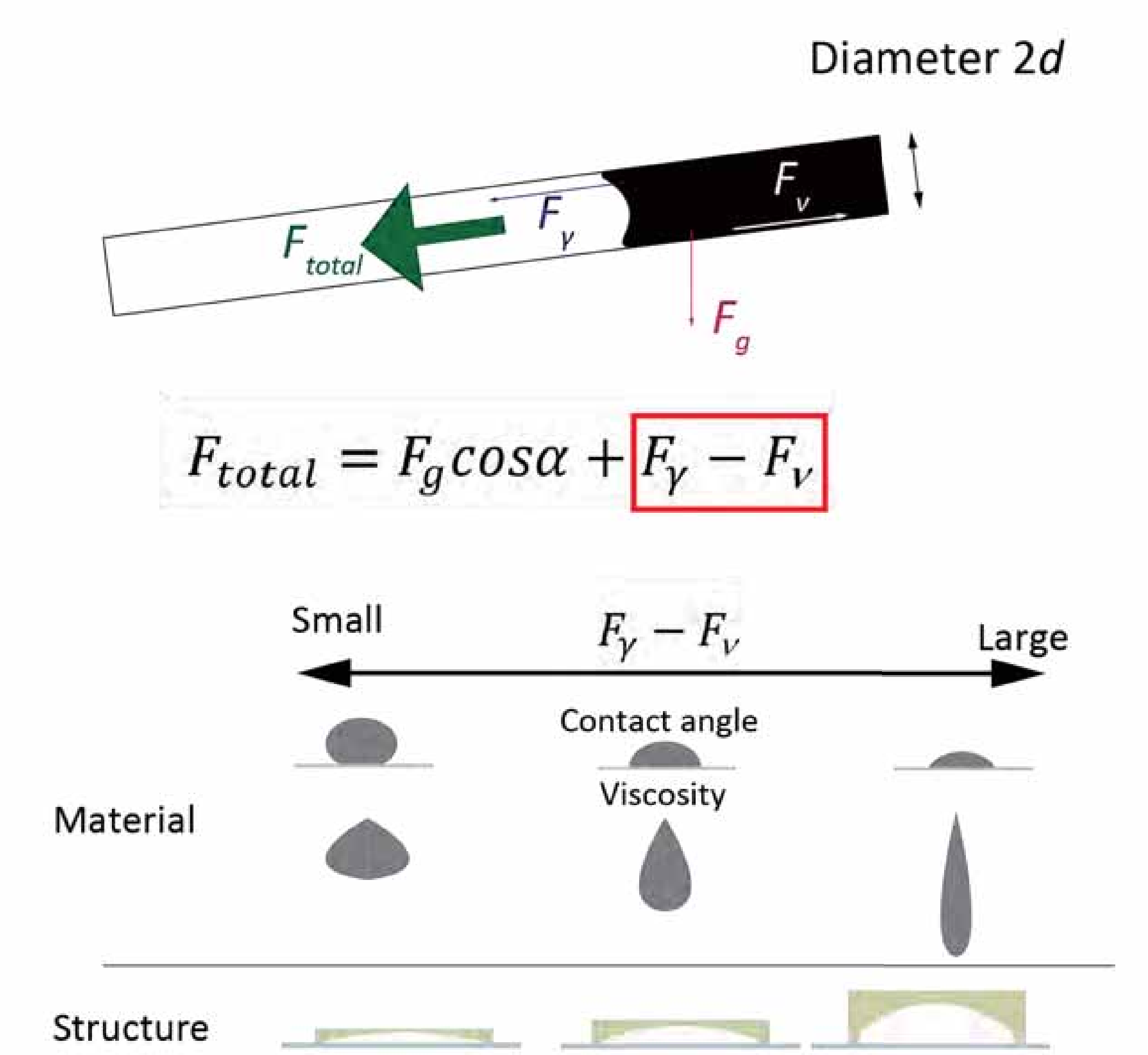

Figure S1. Forces on liquids during tilt, and material and structural properties.

The combined force on the fluid under tilting is

$$F_{total} = F_g cos\alpha + F_\gamma - F_v, \tag{1}$$

where F_g is the gravity,F_γ is the attraction due to wetness, F_v is the resistance due to viscosity, and α is the tilt angle.

About F_γ

The fluid flow path is approximated as a straight circular tube with a cross-sectional radius *d*. The pressure difference between the gas and liquid at the liquid interface ΔP is described as follows:

$$\Delta P = \frac{2\sigma cos\theta}{d}, \tag{2}$$

where σ is the surface tension and θ is the contact angle.

By setting the cross-sectional area of the circular tube as δS,

$$F_\gamma = \Delta p \delta S. \tag{3}$$

F_γ is described as follows using $\delta S = \pi d^2$ and Equation (2) and (3):

$$F_\gamma = 2\pi d\sigma cos\theta. \tag{4}$$

About F_v

The pipe friction coefficient under laminar flow conditions λ is

$$\lambda := 64/Re. \tag{5}$$

The pipe friction coefficient considering the effect of wetting is λ_θ, and a correction factor *k* due to wetting is introduced.

$$\lambda_\theta = k\lambda \tag{6}$$

$$k = \frac{(cos\theta + 1)}{2}, \tag{7}$$

where $k = 1$ at $\theta = 0°$, $k = 0$ at $\theta = 180°$, and *k* takes the values from 0 to 1. Moreover, $\lambda_\theta = \lambda$ at $\theta = 0°$ and fluid slides perfectly on the pipe wall at $\theta = 180°$.
The viscous resistance in the pipe F_v is described as follows using the Darcy–Weisbach formula:

$$F_v = \frac{\lambda_\theta L \rho u^2}{2d} \delta S. \tag{8}$$

Using Equation (5) to (8),

$$F_v = \frac{L\rho u^2}{2d} \cdot \frac{(cos\theta + 1)}{2} \cdot \frac{64}{Re} \delta S, \tag{9}$$

and because $\delta S = \pi d^2$,

$$F_v = \frac{\pi d L\rho u^2}{2} \cdot \frac{(cos\theta + 1)}{2} \cdot \frac{64}{Re} \tag{10}$$

$$Re = \frac{\rho u d}{\mu} \tag{11}$$

$$F_v = 16\pi L u\mu(cos\theta + 1). \tag{12}$$

From the above, the combined force F_{total} received by the fluid in the inclined pipe is

$$F_{total} = F_g cos\alpha + 2\pi d\sigma cos\theta - 16\pi L u\mu(cos\theta + 1). \tag{13}$$

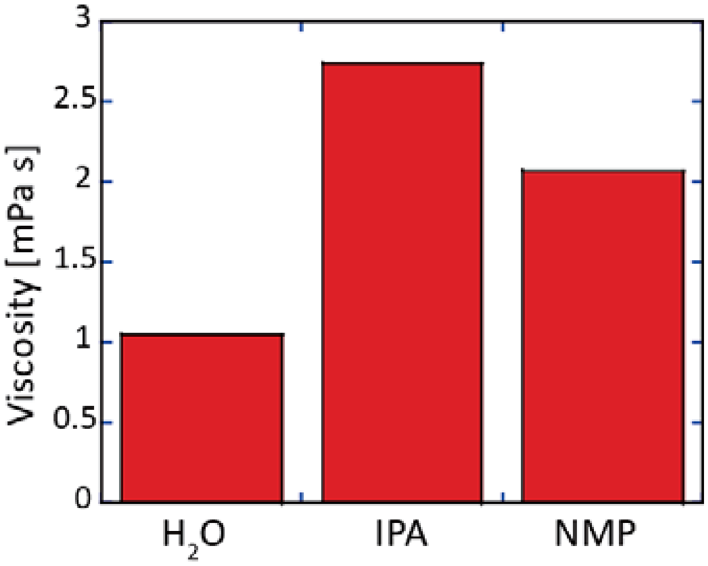

Figure S2. Viscosity of polar solvents H_2O, IPA, and NMP.

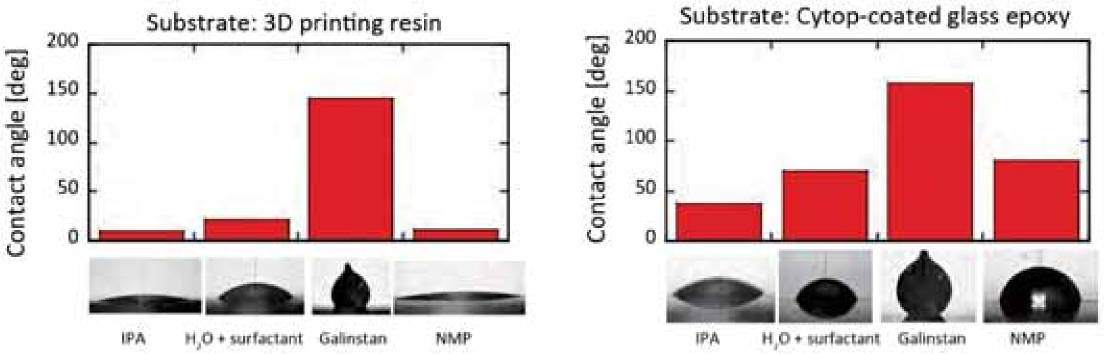

Figure S3. Contact angles. a) Contact angle between shell material and liquid. b) Contact angle between substrate material and liquid.

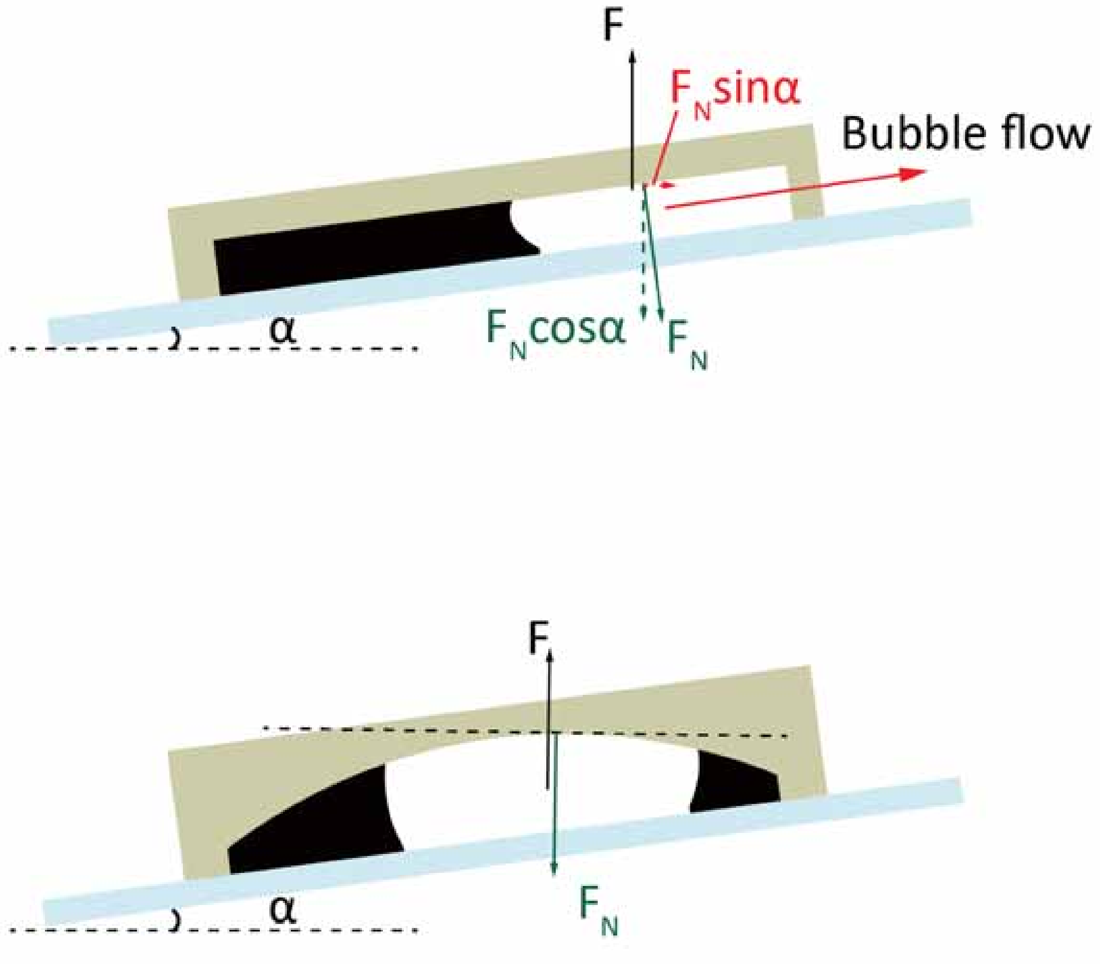

Figure S4. Stagnation of air bubbles due to arc shape.

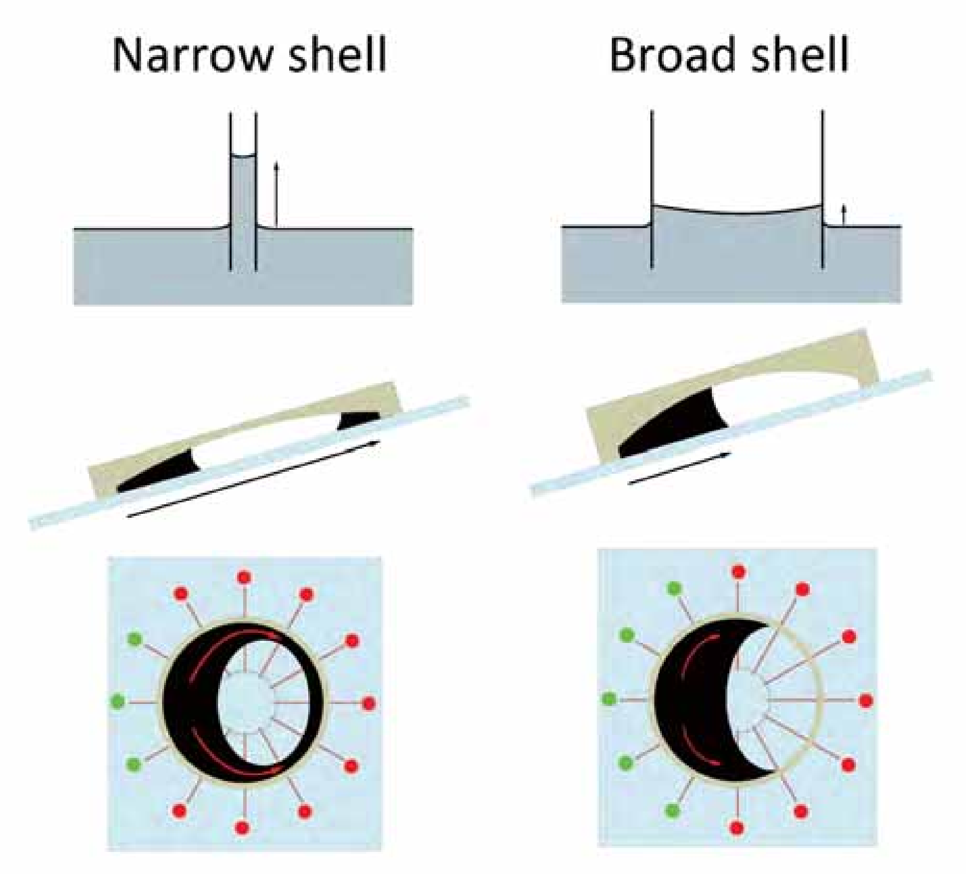

Figure S5. Difference in liquid wetting according to shell space.

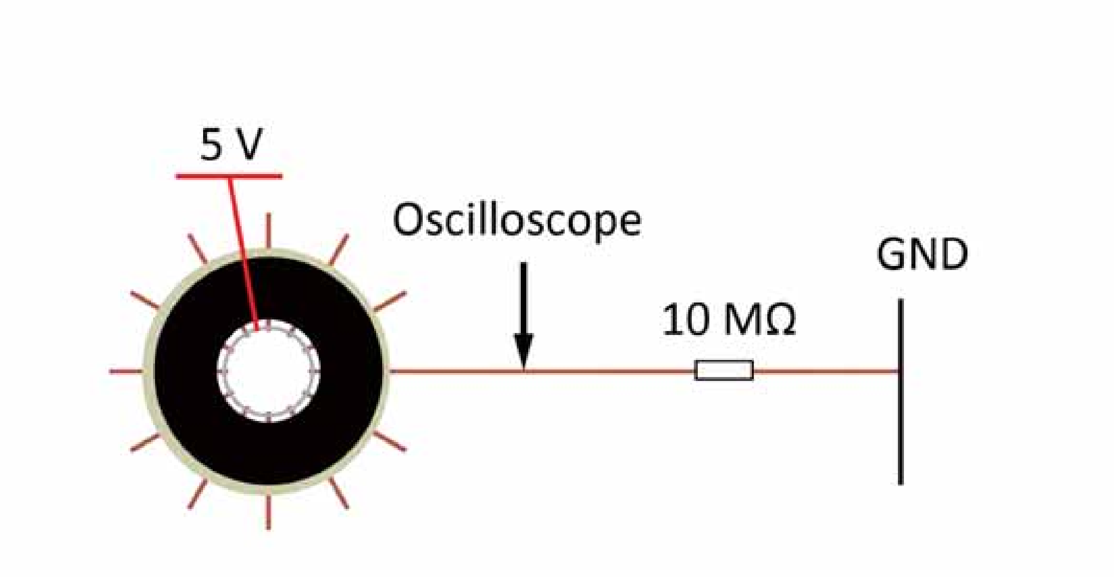

Figure S6. Measurement method of unidirectional tilt test.

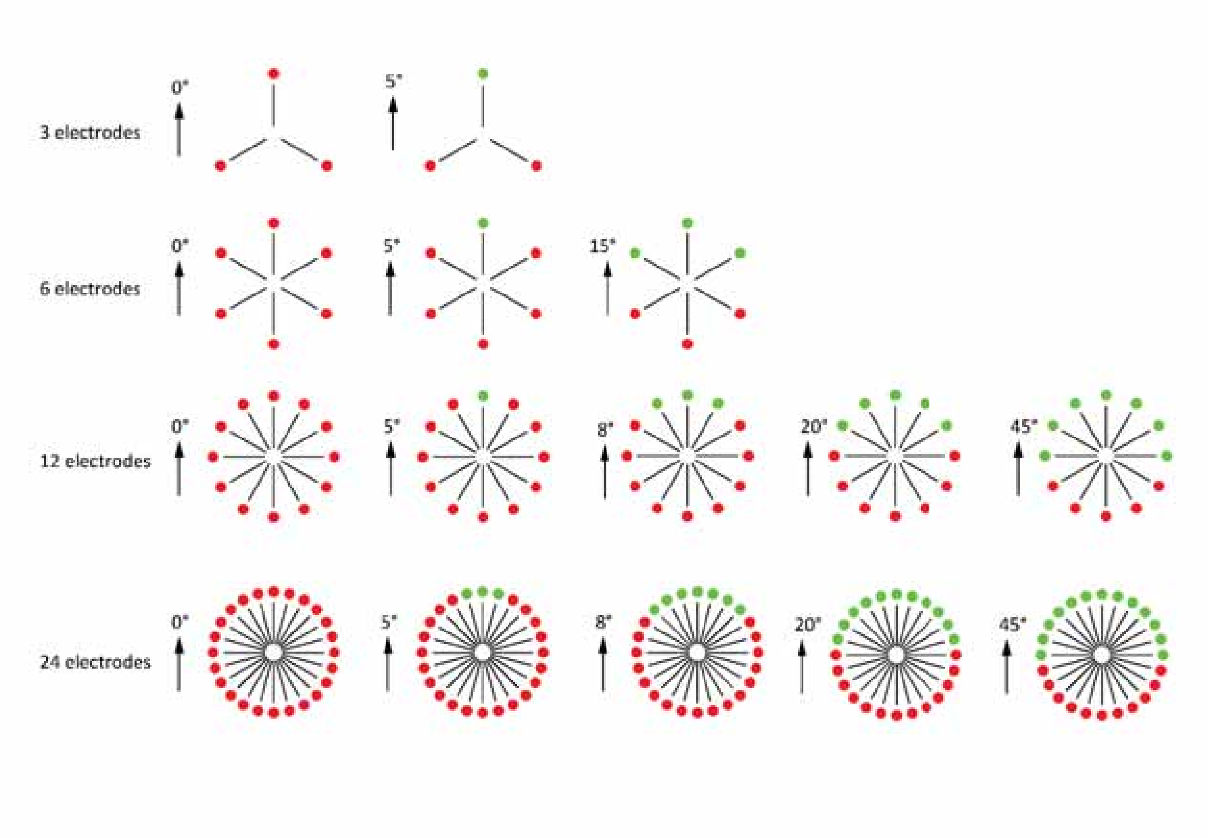

Figure S7. Relationship between number of wires and resolution.

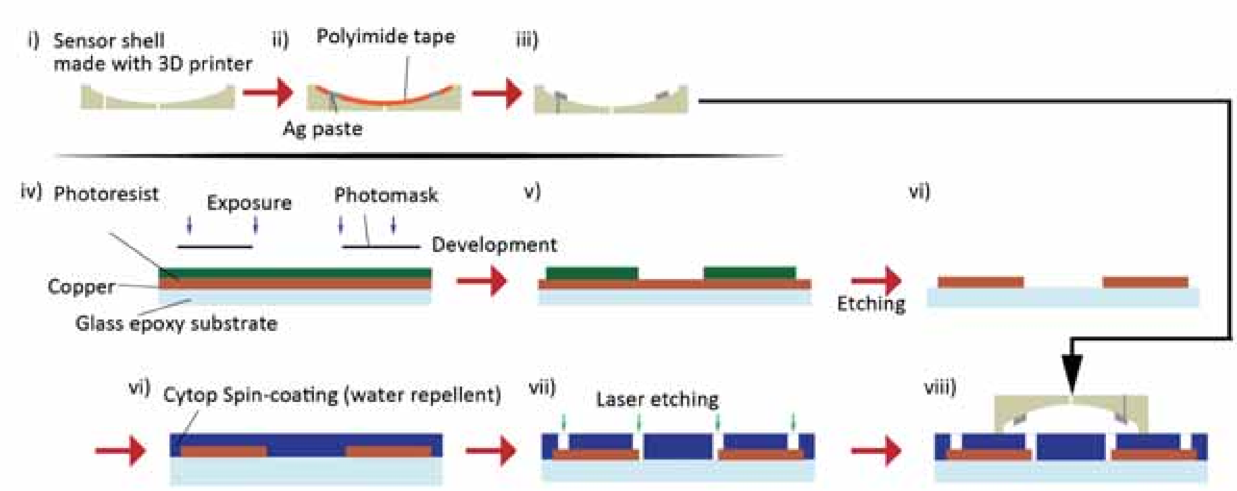

Figure S8. Fabrication method of tilt sensor.

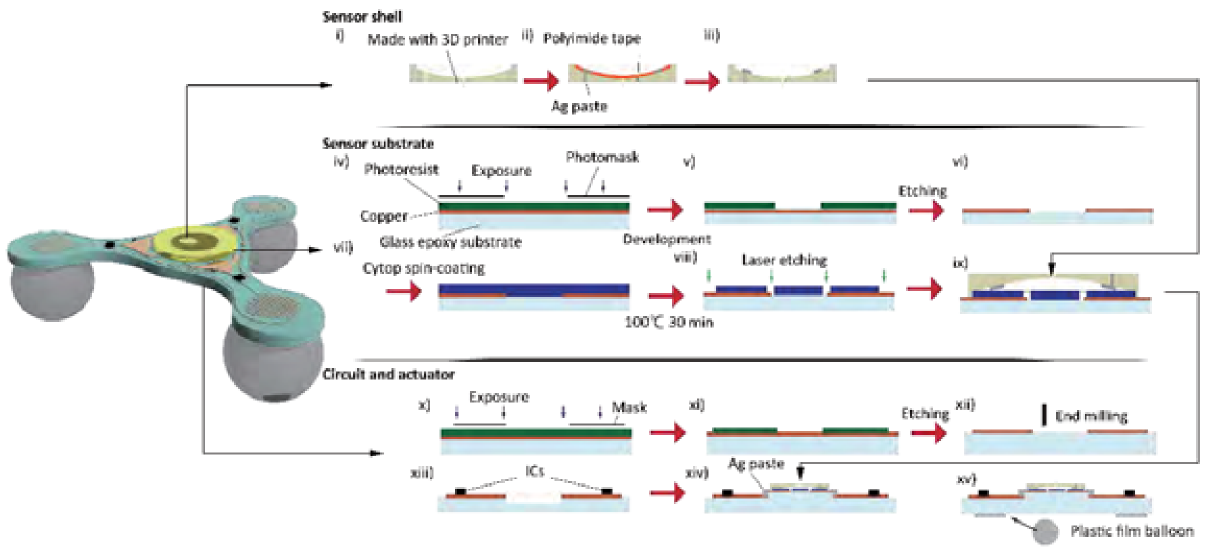

Figure S9. Fabrication method of thermal actuator using tilt sensor.

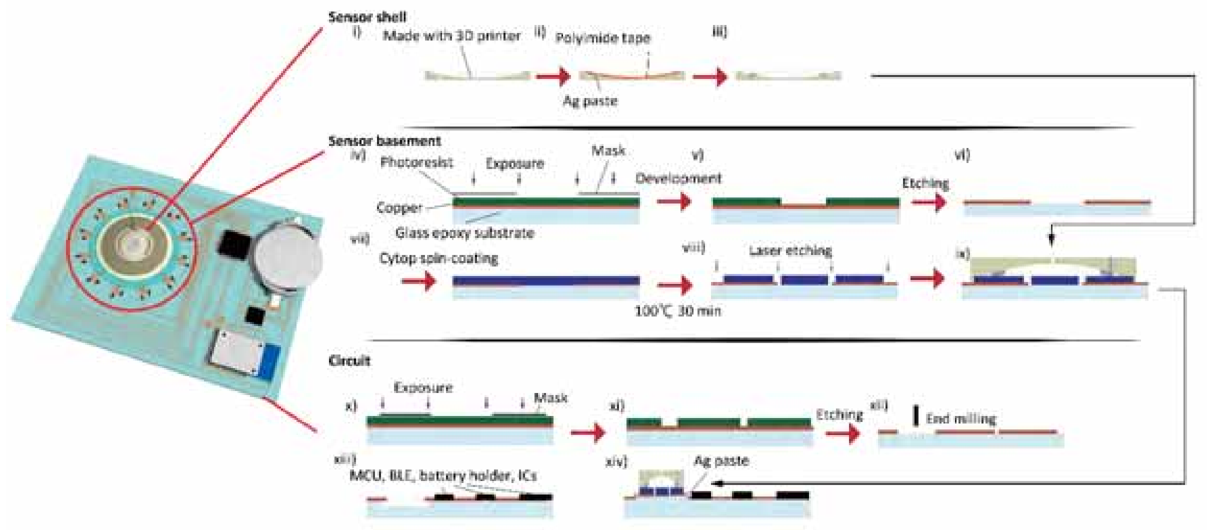

Figure S10. Fabrication method of head-turning tracking wearable device.

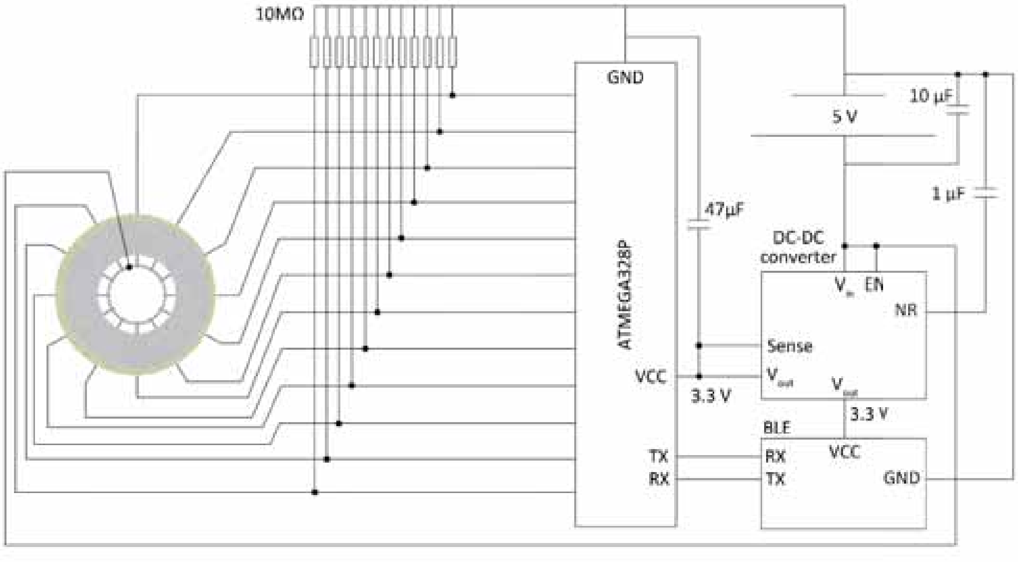

Figure S11. Circuit of head-turning tracking wearable device.