Two-axis Tilt Angle Detection based on Dielectric Liquid Capacitive Structure

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Abstract— This paper presents the design, fabrication, and characterization of a two-axis tilt angle sensor based on the dielectric liquid capacitive sensing structure. The sensor consists of five electrodes. One electrode serves as the exciting electrode and two pairs of electrodes as sensing electrodes, which are arranged at identical positions surrounding a glass cylinder tube, which is partly filled with dielectric liquid. Based on this unique arrangement, the proposed sensor can detect two components of tilt angle in x-axis and y-axis, simultaneously. A computational simulation and experimental measurements are performed to study the performance of the sensor. The numerical simulation is carried out with a finite element analysis using COMSOL. A prototype of the sensor was fabricated, and its performance was evaluated. The tilt angle sensor was employed on a printed circuit board with a conditioning circuit, which consisted of a 170 kHz sine wave generator, pre-amplifiers, rectifiers, and low pass filters. The experiment results confirmed that the tilt angle sensitivities to x-axis and y-axis are 18.2 mV/° and 58.2 mV/° respectively, with cross-axis sensitivity being less than 5.5% in the linear range. The measured tilt angle resolutions are 0.55° and 0.17° on the x-axis and y-axis respectively.

Index Terms— Capacitive sensor, fluidic sensor; tilt angle measurement

1. Introduction

Tilt angle sensors are mainly applied to measure the horizontality of a system or object and have been widely used in robotics, human body motion detection, transportation vehicles, industrial equipment, industrial automation, intelligent platform, machining, and other important fields [1]–[4].

There are several kinds of commercial sensor for tilt angle measurement, which can be divided into two main kinds: solid-based and fluid-based mechanisms, depending on their working principles. The research on sensors of solid-based tilt angle has matured over the course of many applications. This kind of sensor consists of a proof mass suspended by a cantilever, spring, hinged bar or roller ball [5]–[9]. When the sensor body rotates around vertical or horizontal reference orientation, under the influence of the gravity, the suspended solid structure is deformed; this deformation is measured in terms of tilt angle. Recent technological advancements in the manufacturing of tilt sensors have improved the sensing accuracy, reduced the fabrication cost, increased the working lifetime, and enhanced their performances [10]–[13]. The main issue for these sensors is that it is easy for them to get damaged by the external forces, such as vibration or mechanical shock.

The sensor of fluid-based tilt angle utilizes the movement of fluidic structure to sense the gravitational acceleration. To be moved by gravity, the fluid density in a container is not equally distributed. It is done by either locally heating a homogenous liquid or by using a mixture of immiscible fluids which can be liquid-air or liquids with different densities [14]–[26]. Locally heating fluids (thermal convective tilt sensor) is usually done using gas-based sensors; its principle works by transferring heat due to convection. Using a constant current, the gas inside the sealed chamber is heated, and the temperature profile moves in concordance with the applied inclination.
Such kind of sensor has simpler structure without proof mass suspended as a part of the sensor and stronger shock resistance, compared to solid-based tilt angle. Even though this kind of sensor can be easily affected by environmental temperature and is low in measurement precision. Moreover, the heaters use high power, owing to the requirement of temperature, for sensing. In contrast, mixing of immiscible liquids or partly filled liquid-air (fluidic tilt angle sensor) has many advantages, such as high sensitivity, corrosion, moisture, and shock resistance [14], [27], [28]. The output voltage of this kind of tilt sensors is obtained most commonly by transducing the physical changes of its medium to an electrical signal based on resistance [23], capacitance, inductance [14], piezoelectric [4], resonant [29] or optical parameters [3], [30]. Among them, capacitive type with linear and analog outputs [2], [25], [26], [31]–[34] is mostly used. Besides, capacitive sensing, in comparison with other detection principles of tilt sensor, has many advantages such as simplicity, noncontact measurement, long-throw linear displacement, and the design and fabrication process are significantly simpler than their counterparts. However, most of these sensors are single-axis sensing structure [33]–[35].

There is an increasing demand of high-performance tilt angle sensor for emerging applications, especially medical and automotive applications. In this paper, we introduce a two-axis tilt sensor based on a dielectric liquid capacitive configuration with differential capacitively coupled contactless conductivity detection (DC4D) technique. The unique arrangement of only four sensing electrodes sharing a single exciting electrode allows us to detect dual axis simultaneously with low cross sensitivity, thereby overcoming the single-axis limited concept in the previous work [36]–[38]. This configuration is robust, highly accurate, and easy-to-build with inexpensive and commercially available electronics instead of research-grade tools. Although recent advanced

![Fig. 1. Proposed two-axis tilt sensor based on dielectric liquid capacitive structure.](image_url)

**Tab.1. Parameters of the proposed two-axis tilt angle sensor (see fig.1b)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mm)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>L&lt;sub&gt;1&lt;/sub&gt;</td>
<td>10.0</td>
<td>Curvature length of the excitation electrode</td>
</tr>
<tr>
<td>W&lt;sub&gt;1&lt;/sub&gt;</td>
<td>7.5</td>
<td>Length of the excitation electrode</td>
</tr>
<tr>
<td>L&lt;sub&gt;2&lt;/sub&gt;</td>
<td>5.0</td>
<td>Curvature length of the x-axis sensing electrodes</td>
</tr>
<tr>
<td>W&lt;sub&gt;2&lt;/sub&gt;</td>
<td>7.5</td>
<td>Length of the x-axis sensing electrodes</td>
</tr>
<tr>
<td>L&lt;sub&gt;3&lt;/sub&gt;</td>
<td>7.0</td>
<td>Curvature length of the y-axis sensing electrodes</td>
</tr>
<tr>
<td>W&lt;sub&gt;3&lt;/sub&gt;</td>
<td>17.3</td>
<td>Length of the y-axis sensing electrodes</td>
</tr>
<tr>
<td>t</td>
<td>0.2</td>
<td>Thickness of the electrodes</td>
</tr>
<tr>
<td>L</td>
<td>25.0</td>
<td>Total length of the sensor</td>
</tr>
<tr>
<td>D</td>
<td>11.0</td>
<td>Diameter of the sensor</td>
</tr>
<tr>
<td>g</td>
<td>0.5</td>
<td>Thickness of the glass wall</td>
</tr>
</tbody>
</table>
microfabrication technology has reduced the cost and the size of the tilt sensor, the burden of the initial installment and prototyping could delay the transformation of a theoretical idea to a realistic production [9], [39]–[42]. The proposed sensor which has simple structure and is easy to be fabricated has been briefly presented in our previous work [43]. In this paper, details of design, simulation, and characterization of the sensor are presented. With its simplicity, the sensor can be customized to fit the various applications.

2. Dielectric Liquid Capacitive Sensor for Tilt Angle Measurement

A. Design and Working Principle

The first report on capacitively coupled contactless conductivity detection (C4D) in microfluidic systems was published in 2001 by Guijt et al. [44]. In this paper, in order to avoid various difficulties commonly found in the contact method and to improve the sensing detection limit, this approach has been utilized.

The structure of the proposed sensor is shown in Fig. 1(a). The dielectric liquid capacitive sensor is mounted on a printed circuit board (PCB). The sensor is constructed from an air-liquid two-phase borosilicate glass cylinder surrounded by five electrodes. The cylinder contains gasoline (permittivity of 2) and air (permittivity of 1), and is completely sealed by epoxy to prevent gasoline from evaporating or leaking. Gasoline was chosen because it has low surface tension (0.0198 N/m) and viscosity (0.6 mPa.s), which will allow the bubble to move and settle quickly while in contact with the borosilicate glass. Parameters of these materials are shown in Tab. 2.

The borosilicate glass has diameter of 11.0 mm, length of 25.0 mm, and thickness of 0.5 mm. The curvature length and length of the excitation electrode, x-axis sensing electrodes and y-axis sensing electrodes are 7.5 mm and 10.0 mm, 7.5 mm and 5.0 mm, and 17.3 mm and 7.0 mm, respectively. The thickness of the electrodes is 0.2 mm. The geometry parameters of the sensor and properties of the materials used in this work are listed in Tab. 1.

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Fig. 2. Working principle of the liquid capacitive tilt sensor. (a) 3D drawing with one excitation electrode and four sensing electrodes; (b) C₁ and C₂ capacitor on the x-axis tilt scenario. The differential capacitance value (C₁ − C₂) changes when liquid surface is rotated relative to the electrodes; (c) C₃ and C₄ capacitor on the y-axis tilt scenario with the change of (C₃ − C₄).

Tab. 2. Properties of some materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Properties</th>
<th>Air</th>
<th>H₂O</th>
<th>Gasoline</th>
<th>Glass</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative permittivity</td>
<td></td>
<td>1.0</td>
<td>80.1</td>
<td>2.0</td>
<td>4.6</td>
<td>conductor</td>
</tr>
<tr>
<td>Surface tension (mN/m)</td>
<td></td>
<td>-</td>
<td>72.8</td>
<td>19.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Viscosity (mPa.s)</td>
<td></td>
<td>18E-3</td>
<td>1.0</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Conductivity (S/m)</td>
<td></td>
<td>3E-15 to 8E-15</td>
<td>~5.5E-6</td>
<td>25E-12</td>
<td>~1E-15</td>
<td>58.5E6</td>
</tr>
</tbody>
</table>
and Tab. 2, respectively.

In the previous work, the electrodes were placed inside microchannel and protected by an insulating layer (i.e., thin SiO$_2$ or PDMS layer). Such deposition process is costly and time consuming, and the selection of material is also limited. In addition, all the electrodes had to be placed in the same plane [45][46]. In this work, the electrodes are placed outside, the glass tube serves as the protective layer and helps to isolate the electrodes from the liquid medium. Though the thickness of glass tube affects the sensitivity of a single capacitor pair, it has limited effect on sensor performance because C4D is measured in differential sensing mode and the existence of glass thickness can be compensated by the charging level determined at initial state for sensor calibration.

In this design, the volume ratio of liquid and air is 3:1. The electrode underneath the tube serves as the excitation electrode and the rest four serve as the sensing electrodes. The two electrodes $XE_1$ and $XE_2$ are the sensing electrodes for monitoring the $x$-axis angle and the two electrodes $YE_1$ and $YE_2$ are the sensing electrodes for monitoring the $y$-axis angle (see Fig. 1(b)). These five electrodes make two pairs of differential capacitance of $(C_1 - C_2)$ and $(C_3 - C_4)$ corresponding to the $x$-axis and $y$-axis tilt angles, respectively. The differential capacitances depend on the position of the liquid surface inside the cylinder tube, which changes because of gravity when the sensor is rotated (see Fig. 2). Therefore, differential capacitance of $(C_1 - C_2)$ and $(C_3 - C_4)$ correspond to the tilt angle of the $x$-axis and $y$-axis, respectively (see Fig. 2).

When exciting a sine signal to the excitation electrode, the capacitance of the capacitor constructed by the excited electrode and sensing electrode determines the output voltage, which is the differential voltage between the electrodes. Thus, the tilt angle of the sensor on the $x$-axis and $y$-axis can be monitored by measuring the differential voltage $(V_{C_1} - V_{C_2})$ and $(V_{C_3} - V_{C_4})$, respectively.

It is indeed no difficulty to deploy the same design scheme to a symmetric design (i.e., cubic or sphere). In microfabrication technique where the alignment and production is automated at mass production scale (i.e., wafer level), the symmetricity is easy and guaranteed. In our study, where the conventional mechanics is involved, the design should be simple and lab-made ready. Thus, the cylinder glass was selected. The selection of cylinder allows investigating $x$- and $y$-axis asymmetrically and deepen our understanding. In addition, the cylinder shape is widely available and is compatible with conventional mechanics.

**B. Modeling and Simulation**

In this work, the finite element method (FEM) is utilized to investigate the performance of the proposed two-axis tilt angle sensor, which is based on dielectric liquid capacitive sensing structure. The capacitive tilt sensor is
modeled and simulated using COMSOL software to analyze the capacitor with curved electrodes and nonuniform relative permittivity medium (liquid-air two phases dielectric medium). The dielectric constant of the fluid is assumed value of 2 (i.e., gasoline) without counting surface tension effect between liquid and cylinder wall.

The device was modeled as a glass cylinder (Fig. 3) with copper electrodes placed outside and liquid initially occupied 75% of the cylinder volume. The air space surrounding device is truncated by sphere whose outer surface is applied with zero charge boundary condition (Fig. 3(a)). A DC voltage is applied to electrode to determine the capacitance. The sensing electrodes are set at 7.0V and the underneath electrode was grounded (Fig. 3(b)).

The tilted state was mimicked by rotating the device frame relatively with the liquid level, which stays the same as the initial state. Inside the device, the capacitance and the electrical field will be affected by the different voltage between electrodes and their relative position with the liquid level. The capacitance of two sensing
electrodes versus exciting electrode was integrated over their surface and their difference was extracted.

In this simulation, we simplify the concept by claiming non-conductive liquid. Non-contaminated gasoline has a conductivity of ~25 pS/m, so it is rated as a non-conductor. In addition, the model was simplified by ignoring the movement of charge in the liquid, thus the double layer electrode capacitor was not formed. Under the assumption of electrostatic conditions, the surface of each electrode is at the same potential. The other domains of the model were assumed to be the ideal insulators.

Figures 3(c) and 3(d) demonstrate electrical field profiles of the sensor under the x-axis rotation and y-axis rotation, respectively. It shows that the voltage potential of the sensing electrodes is higher than that of the excitation electrode. Fig. 3(c)-left shows the voltage profile when the sensor is in the balanced stage (zeros tilt angle). In this case, the two capacitors are symmetrical. Hence, the differential capacitance between the two sensing electrodes is zero. When the sensor rotates, the relative position of the liquid surface changes and the electrode alters the capacitance of the \( C_1 \) and \( C_2 \). Therefore, the symmetry status between the two electrodes is broken as shown in Fig. 3(c)-right.

Figure 4 presents a simulated capacitance of \( C_1 \) and \( C_2 \) capacitors when the sensor is tilted from -180° to +180° around x-axis. The capacitances of \( C_1 \) and \( C_2 \) are symmetrically changed with respect to the original point. Capacitance \( C_1 \) and \( C_2 \) reach peak value of about 140 fF when tilt angle is -60° and +60°, respectively. When the \( C_2 \) gets the maximum value at about 60° the \( C_1 \) gets the minimum value, and vice versa.

The tilt angle in x-axis can be extracted from the difference value of \( (C_2 - C_1) \). Figure 5 shows the differential capacitance \( (C_1 - C_2)_{x\text{-axis}} \) versus the input rotation angle around x-axis (black solid line). The sensor has a linear response in the range from -60° to +60° with simulated sensitivity of 0.45 fF/°, though the measurable range is from -70° to +70°. In the other ranges, the response is nonlinear but still can be used to measure the rotation angle.

Besides the effect of x-axis rotation, the differential capacitance \( (C_1 - C_2) \) is also affected when y-axis tilt angle is applied, known as the cross-talk. The differential values of \( (C_1 - C_2)_{x\text{-axis}} \) and \( (C_1 - C_2)_{y\text{-axis}} \) versus input x-axis and y-axis tilt angles are shown in black solid and red dash lines, respectively in Fig. 5. As can be seen, the cross-talking value of \( (C_1 - C_2)_{y\text{-axis}} \) is much smaller than that \( (C_1 - C_2)_{x\text{-axis}} \), i.e., approximately zero, thanks to the symmetrical arrangement of the sensing electrodes. Therefore, in this case, the cross-talk from y-axis inclination can be ignored.

Similarly, Fig. 3(d) shows electrical field profile of the sensor under y-axis rotation scenario. The voltage profiles when the sensor is at the initial and tilted states are presented in Figs. 3(d)-left, and 3(d)-right. Capacitance values of \( C_3 \) and \( C_4 \) are extracted and plotted in Fig. 6 (green dot-dash and blue dash lines). As can be seen, capacitance values of \( C_3 \) and \( C_4 \) change symmetrically with respect to the original point.

Figure 7 shows differential capacitance value of \( C_3 \) and \( C_4 \). Similar to the x-axis configuration, the \( (C_3 - C_4) \) consists of two components, which are \( (C_3 - C_4)_{y\text{-axis}} \) as the signal and \( (C_3 - C_4)_{x\text{-axis}} \) as the cross-talk. The linear response of this configuration is -20° to +20° on y-axis and sensitivity of 0.85 fF/°. The simulated results also show that the cross-talk \( (C_3 - C_4)_{x\text{-axis}} \) from x-axis inclination is approximately zero, much smaller compared to the \( (C_3 - C_4)_{y\text{-axis}} \), and can be ignored.

From the above analysis, we confirm the working principle of the proposed sensor and its ability to measure two components of tilt angle around x- and y-axis with negligible cross-talks. Experimental assessment on the sensor is presented as follows.

3. Measurement Setups

A sensor prototype was constructed by five copper electrodes and a glass cylinder tube. The cylinder contains 75% gasoline (permittivity of 2) and 25% air (permittivity of 1). Liquid is filled from one end through a hole and the hole is sealed completely by epoxy to prevent gasoline from evaporating or leaking. The copper electrodes were cut by computer numeric control (CNC) and bonded to the outside of the cylinder at desired positions with
A measurement setup was built to investigate the performance of the tilt angle sensor for both \( x \)-axis and \( y \)-axis (see Fig. 8). The proposed tilt capacitive sensor is anchored on a printed circuit board (PCB) with electronic circuits. The PCB is packaged in a shielding box and then positioned on a rotation disk with readout resolution of 0.1°. Tilt angle of the PCB is changed gradually in the interval \(-180° \sim +180°\) by rotating the disk and the corresponding output voltage value is recorded. The output analog signal after the conditioning circuit is routed to a personal computer (PC) by using a National Instruments Data Acquisition (DAQ) and LabVIEW software.

First, the PCB is aligned to characterize tilt angle in \( x \) axis. Then it is rotated 90 degrees in vertical plane to characterize the performance of the sensor in sensing tilt angle in \( y \) axis. Beside the amplitude response on both axes, the cross-talks are also investigated.

The block diagram of the electronic circuit is given in Fig. 9. A 170-kHz sine signal generator is connected to the excitation electrode. The sine generator circuit is a Wien bridge oscillator using an operation amplifier (TL084). The frequency of the oscillator is controlled by resistor \( R \) and capacitor \( C \); output amplitude is adjusted by resistors \( R_1 \) and \( R_2 \). Because the voltage on sensing electrodes changes with their corresponding capacitance, \( x \)-axis and \( y \)-
axis tilt angle can be monitored by measuring amplitude of the differential voltage pair \((V_{C1} - V_{C2})\) and \((V_{C3} - V_{C4})\), respectively.

The conditioning circuits convert current signals to the voltage by using four resistors \(R_{e1}, R_{e2}, R_{e3}\), and \(R_{e4}\). Each voltage signal is then pre-amplified before applying to the differential amplifier. An instrumentation amplifier is employed as the differentiators. Amplitude demodulation circuit consists of a full wave precision rectifier and a RC passive low-pass filter (LPF) with cut-off frequency of 16 Hz. Output voltage of the LPF circuits are the outputs of the tilt angle sensor. In this work, the differential amplifier is used not only for taking the differential voltage between each voltage pair but also rejecting the common noise such as industrial noise of 50 Hz frequency, and other external-noise sources.

4. Experimental Results and Discussion

Relations between measured output voltage and tilt angle in \(x\)-axis and \(y\)-axis are shown in Fig. 10. The measured voltages have similar shapes and responses with the simulated results. The output signals are symmetrical with respect to the original point. The inset shows the output voltage signal of the sensor at zeros tilt angle with voltage swing of ±5 mV. As can be seen, the \(x\)-axis configuration has a better linear response than the \(y\)-axis case. It is because the shape of the cylinder is asymmetric.

The measured \(x\)-axis voltage has a perfect symmetric form and can be divided into three areas as described in the simulation results where the measurement range of this fabricated sensor is from \(-80^\circ\) to \(+80^\circ\). The output voltage reaches peak value of about 1150 mV at the tilt angle of \(80^\circ\). The measurement range of this \(x\)-axis configuration is larger than that of the simulation. The difference between the simulation and experiment may due to the ratio of air/liquid and capillary effect of investigated liquid.

A zoom-in draw with linear fitting around original point of the measured data is presented in Fig. 11. The \(x\)-axis configuration has a linear range in the range of \(-60^\circ\) to \(+60^\circ\) (correlation coefficient of 0.999). The sensitivity of the measured data in this range is 18.2 mV/°.

Noise is unavoidable in all electrical measurement systems, including external noise, conducted noise, and intrinsic noise (thermal noise, 1/f noise). In our case, noise is any voltages that occur when there is no tilt angle applied to the sensing structure. Total measurement error measured at zero tilt angle is about ±5 mV (see Fig. 11), therefore the measurement resolution, which is defined by measurement noise divide by sensitivity, is about 0.55°. The measured error came from the thermal noise, cross-talk noise, common noise, industrial noise. Figure 12 shows crosstalk voltage of the two configurations. The cross-talk voltages are estimated less than 5.5% in the linear range, i.e., quite small to compare with the corresponded signals. In simulations, crosstalk is evaluated to be small and ignorable. The difference between simulation and measurement might come from a slight mispositioning of \(x\)-axis and \(y\)-axis sensing electrodes on the cylinder tube.

The response of the \(y\)-axis configuration is also shown in Fig. 10 and Fig. 11. The measurement range is from \(-30^\circ\) to \(30^\circ\) with the linear range is from about \(-16^\circ\) to \(+16^\circ\) (correlation coefficient of 0.994). This measured data is matched with the simulation showing in Fig. 7. The measured sensitivity and resolution of this configuration are about 58.2 mV/° and 0.17°, respectively.

The proposed structure reveals its ability to measure two components of tilt angle in \(x\)-axis and \(y\)-axis, simultaneously. However, the measurement ranges of tilt angle in \(x\)-axis is wider than that in \(y\)-axis. This came from the asymmetric in geometry of the cylinder tube. Tab. 3 summaries the characteristics of several typical tilt sensors in the literature and in our work. Each design has its own advantages as discussed in Introduction part of the manuscript. Thus, it is not easy to significantly improve one characteristic without trading off the others. Based on these data, the sensor in this work can be considered as the same group with its references.

According to the obtained results, the proposed tilt sensor can be used for many different applications with two different adaptable detecting ranges and sensitivities. The different structures of the tilt sensor, such as the
position of the electrodes and their dimensions, can affect to its characteristics. Therefore, the performance of the proposed tilt sensor can be further improved by optimizing structural design such as the shape of the container, dimensions and position of the electrodes. The results on manipulating the parameters of sensor structure will be reported in another work.

5. Conclusion

The design, fabrication, and characterization of a two-axis tilt angle sensor based on dielectric liquid capacitive sensing structure were presented. The sensor consists of five electrodes arranged at designated positions surrounding a glass cylinder tube, which is partly filled with the dielectric liquid. With this unique arrangement, the proposed sensor can detect two components of tilt angle in x-axis and y-axis, simultaneously. Based on simulated results, a prototype of the proposed sensor was fabricated and characterized. Experimental results confirmed the performance of the sensor. Tilt angle sensitivities to x-axis and y-axis are 18.2 mV/° and 58.2 mV/°, respectively, with cross-axis sensitivity less than 5.5% in the linear range. The measured tilt angle resolutions are 0.55° and 0.17° on x-axis and y-axis, respectively. This proposed sensor is robust, cost effective, and can be used in many applications.
Tab. 3. Characteristics of tilt sensors

<table>
<thead>
<tr>
<th>Principle</th>
<th>Ref.</th>
<th>Detection method</th>
<th>Degree of freedom</th>
<th>Sensitivity (resolution)</th>
<th>Measurement range</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Moubarack-2012 [12]</td>
<td>Piezoelectric</td>
<td>Single</td>
<td>1.9 mV/90°</td>
<td>±90°</td>
<td>Simulation only</td>
</tr>
<tr>
<td></td>
<td>Paulo-2012 [13]</td>
<td>Optical</td>
<td>Dual</td>
<td>1.38 – 1.43 pm/°</td>
<td>+90°</td>
<td>High grade analyser</td>
</tr>
<tr>
<td></td>
<td>Yang-2015 [30]</td>
<td>Optical</td>
<td>Dual</td>
<td>0.074 nm/°</td>
<td>0 - 40°</td>
<td>High grade analyser</td>
</tr>
</tbody>
</table>

| Gas-based | Han-2017 [22] | Resistive | Single | ∆R/R° = 875 ppm/° | ±90° | At 50 µW heating |
| | Dau-2006 [28] | Resistive | Dual | 0.12 mV/° | ±90° | MEMS process |

| Liquid-based | Subir-2014 [3] | Optical | Single | 0.8° (0.09°) | ±90° | Simple |
| | Lin-2008 [14] | Impedance | Single | 19 mV/° (0.3°) | ±160° | Impedance analyser |
| | Zou-2013 [29] | Resonant | Single | 50.06 Hz/° | ±90° | MEMS process |
| | Welch-2013 [24] | Optical | Dual | 0.075 µA/° | ±45° | MEMS process |
| | Jung 2007 [25] | Capacitive | Single | 50 mV/° | ±60° | MEMS process |
| | Chiu 2015 [26] | Capacitive | Single | 0.48 mV/° | ±90° | CMOS-MEMS process |
| | Choi-2012 [23] | Capacitive | Dual | 50 mV/° | ±70° | MEMS process |
| | Gou-2016 [32] | Capacitive | Single | 0.129 pF/° | ±40° | MEMS process |
| | This work | Capacitive | Dual | x-axis: 18.2 mV/° (0.55°) | x-axis: ±60° | MEMS process |
| | | | | y-axis: 58.2 mV/° (0.17°) | y-axis: ±16° | MEMS process |

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