NOISE REDUCTION BASED ON A NEW SENSOR MOUNTING METHOD IN TILT MEASUREMENT WITH ANALOG ACCELEROMETER

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ABSTRACT this paper introduces a new sensor mounting method to reduce the effects of interference in measuring the roll angle. Using a triaxial accelerometer to measure two tilt angles, roll and pitch, is a well-known technique. An analog accelerometer allows us to process signals in real time without limiting resolution, sampling rate, and data synchronization. The angles are calculated from absolute voltages of the sensor outputs. Therefore, the noise on connection wires can affect the measurement accuracy. Shielded cables and shielding systems can isolate the analog signals from external noise sources. Preprocessors can convert the signals before transmitting. However, the main drawback of these solutions is the big size, which should be avoided in some applications. Filters can extract the signals buried in noise without changing the hardware. Nevertheless, we need to consider the time delay in high speed systems. In this study, we mounted the accelerometer on a new orientation and calculated the tilt angles by new equations. The new mounting orientation is defined based on the conventional one, where the coordinate axes of the sensor are parallel to those of the measured object, and a special rotation matrix. In the new formulas, the roll angle is computed from the differential voltages among the sensor outputs. Hence, the effects of external noise can be strongly reduced when balanced lines are utilized for the signal connections. We verified the method by simulation with two virtual accelerometers and a noise source. The simulation results showed the expected improvement. The effects of noise were almost rejected in the roll angle, whereas the pitch angle had no improvement. We can apply this study in many applications which require the roll angle only. If a further study confirms the same results by experiments, the applicability of analog accelerometers can be expanded by a simple way.

1. INTRODUCTION

Tilt measurement is necessary for many fields. Tilt angles can be used as the primary data for: calculating the angles of human joints; sensing the inclination of handheld devices; indicating pitch and roll of vehicles, sail boats, aircraft; monitoring the boom angle of cranes and material handlers, etc. In many applications, triaxial accelerometers in micro-electro-mechanical systems (MEMS) can be used as the inclination sensors.

Tilt sensing with MEMS is based on the direction of gravity. In general, an accelerometer is mounted in parallel with coordinate axes of the measured object. The two tilt angles which relative to the horizontal plane can be calculated from Cartesian components of the gravitational vector (Pedley, 2013). When the sensor is stationary or nearly stationary, the magnitudes of these components are proportional to the absolute output voltages of the triaxial accelerometer. The sensor output can be in either analog form or digital values.

In comparison with digital accelerometers, analog sensors have both advantages and drawbacks. The digital accelerometers are generally immune to the external noise. However, their integrated analog-to-digital converters (ADC) have limited resolutions and limited sampling rates. In addition, we cannot control the starting time of each conversion. In contrast, the analog accelerometers allow us to flexibly process signals. We can convert the signals to the digital form without the above limitations by using an external ADC. The external ADC allows us to synchronize its conversions with following processing steps in some applications. We can also process the analog signal directly to maximize the response speed (Constandinou & Georgiou, 2008). However, when working with the absolute voltages of analog sensors, the influence of external noise is one of major challenges.

In order to reduce the influence of noise, there are some common methods such as: using shielded cables and shielding systems; converting the signal before transmitting the data by preprocessors; or adding filters. These solutions, however, may be not suitable for some applications which require minimum sensor mounting space and/or high speed response (Höller, et al., 2009).

This paper introduces a new solution to work with the analog accelerometers in real time without the need for additional hardware components. Instead of the conventional mounting orientation, an analog accelerometer is mounted on a special orientation; the corresponding calculation formulas are also changed. In the new equations, the roll angle is computed from the differential voltages among the sensor outputs. The same fluctuation in these voltages disappears in the final result because of the signal subtractions. Hence, when we use the balanced lines to transmit the output signals of the sensor, the effects of the external noise can be strongly reduced. In contrast, the pitch angle is still calculated from the absolute voltages. Therefore, there is no improvement in this angle. The proposed method has been confirmed by simulations.

2. METHODS

2.1 Sensor Mounting Orientations

Tilt angles, roll and pitch, are two of three Euler angles in yaw-pitch-roll sequence (Diebel, 2006). The value of each angle can be determined after rotating the sensor from the reference frame to the current orientation. The order of rotations is about Z-axis first, after that about Y-axis, and finally about X-axis. The conventional mounting orientation (XYZ frame) of the accelerometer is in parallel with the axes measured object. The reference frame is the initial position, with the positive Z-axis in the vertically downward direction. Figure 1 illustrates an example in which the tilt angles of a flexible endoscopic are measured for horizon stabilization.

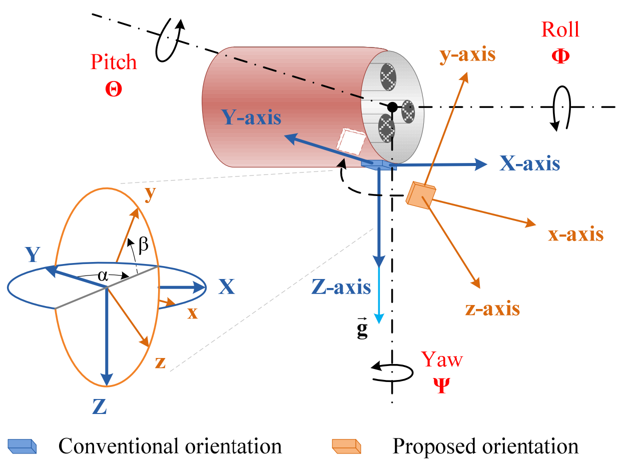

Fig. 1 Definition of the tilt angles and two mounting orientations in an application, endoscopic horizon stabilization.

We proposed a new mounting orientation (xyz frame) based on the XYZ frame and a special rotation sequence. Starting from the XYZ frame, we rotated the sensor about the Z-axis by α first, and then about the X-axis by β. The new orientation of the sensor is the xyz frame. In this study, we proposed $\alpha = -54.7°$ and $\beta = -45°$. These angles have the negative values because both rotations are in the clockwise direction when viewed by the observing direction along the y-axis towards the origin.

2.2 Formula Conversions

We built the new calculation formulas based on the rotation matrix. Equation 1 shows the dependence of the gravitational components (on the XYZ frame) on the tilt angles (Pedley, 2013). Here, all gravitational components are measured in the native units of g (g = 9.8 m/s^2). The rotation about the Z-axis and X-axis can be performed by two elemental rotation matrixes. Therefore, the relationship between the gravitational components (on the xyz frame) and the components on the conventional frame is expressed in Eqn. 2.

$$\begin{bmatrix} g_X \\ g_Y \\ g_Z \end{bmatrix} = \begin{bmatrix} -\sin\Theta \\ \cos\Theta\sin\Phi \\ \cos\Theta\cos\Phi \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} g_x \\ g_y \\ g_z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & \sin\beta \\ 0 & -\sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} g_X \\ g_Y \\ g_Z \end{bmatrix} \quad (2)$$

We substituted the given above values for α and β to build the new equations. After the substitution, Eqn. 2 becomes Eqn. 3 in which the approximate values of a and c are 0.577; those of b and $2d$ are 0.816. These denotations are used for visual expression only. The actual calculations use their precise values. By combining the Eqn. 1 and Eqn. 3, we can calculate the tilt angles by Eqn. 4 and Eqn. 5.

$$\begin{bmatrix} g_x \\ g_y \\ g_z \end{bmatrix} = \begin{bmatrix} a & -b & 0 \\ c & d & -\frac{\sqrt{2}}{2} \\ c & d & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} g_X \\ g_Y \\ g_Z \end{bmatrix} \quad (3)$$

$$\tan\Phi = \frac{1}{\sqrt{2}(bc+da)} \frac{a(g_z+g_y)-2cg_x}{(g_z-g_y)} \quad (4)$$

$$\sin\Theta = -\frac{1}{2(bc+da)} \frac{(bg_z+bg_y+2dg_x)}{\sqrt{g_x^2+g_y^2+g_z^2}} \quad (5)$$

2.3 Noise Reduction Ability

The gravitational components are proportional to the voltages of the sensor outputs. In actual, after transmission, the measured voltages (U_m) are the sum of the wanted signals (U) and unwanted noise (n). By using the balanced lines to connect the sensor and the processing circuit, we can assume that the noise presents on the three connections are identical (Johnson & Graham, 2003), as in Eqn. 6. In the other words, they become the common-mode noise. Therefore, the tilt angles can be calculated from the measured voltages by Eqn. 7 and Eqn. 8.

$$\begin{bmatrix} g_x \\ g_y \\ g_z \end{bmatrix} \propto \begin{bmatrix} U_x \\ U_y \\ U_z \end{bmatrix} = \begin{bmatrix} U_{mx} - n \\ U_{my} - n \\ U_{mz} - n \end{bmatrix} \tag{6}$$

$$\Phi = \arctan 2 \begin{bmatrix} \left(a\left(U_{mz} + U_{my}\right) - 2cU_{mx} - 2\left(a - c\right)n \right), \\ \left(\sqrt{2}\left(bc + da\right)\left(U_{mz} - U_{my}\right) \right) \end{bmatrix} \tag{7}$$

$$\Theta = \arcsin \left[-\frac{bU_{mz} + bU_{my} + 2dU_{mx} - 2\left(b + d\right)n}{2\left(bc + da\right)U_m} \right] \tag{8}$$

$$U_m = \sqrt{\left(U_{mx} - n\right)^2 + \left(U_{my} - n\right)^2 + \left(U_{mz} - n\right)^2} \tag{9}$$

Three equations above show the noise reduction ability. In Eqn. 7, the term $2(a - c)n$ is almost eliminated because a and c are roughly equal. This means that the roll angle is almost independent on the effects of noise. In contrast, the external noise still affects the pitch angle in Eqn. 8 because the coefficient of n is nonzero. In practical calculations, because noise is unknown, we used equations in which all terms of n in Eqn. 7, Eqn. 8, and Eqn. 9 disappear.

3. SIMULATION RESULTS

3.1 Simulation Setup

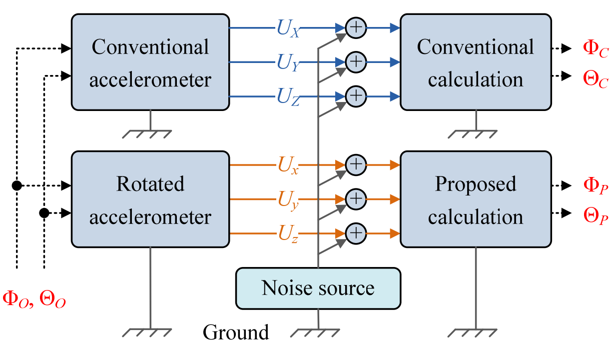

Fig. 2 Simulation model was used to compare the proposed method and conventional method.

We compared the proposed method and the conventional method by simulations. The simulation model contains two virtual accelerometers. The first one is the sensor mounted on the conventional orientation, while the second one creates the data of sensor mounted on the proposed orientation. These virtual sensors generate the outputs based on the original tilt angles, Φ_O and Θ_O. The common-mode noise is added to all sensor outputs. We used a white noise source whose intensity is adjustable. The conventional method (Pedley, 2013) is used as the reference method to calculate Φ_C and Θ_C, while the proposed method computes Φ_P and Θ_P. We evaluated the results based on the differences between each computed angle and the corresponding original angle.

3.2 Simulation Results

The simulations were performed with a series of tilt angles under the quasi-static conditions. Firstly, when noise is zero, all differences between the computed angles and the original values are equal to zero, as shown in Fig. 3. These results confirmed the possibility of the proposed algorithm in angle calculations.

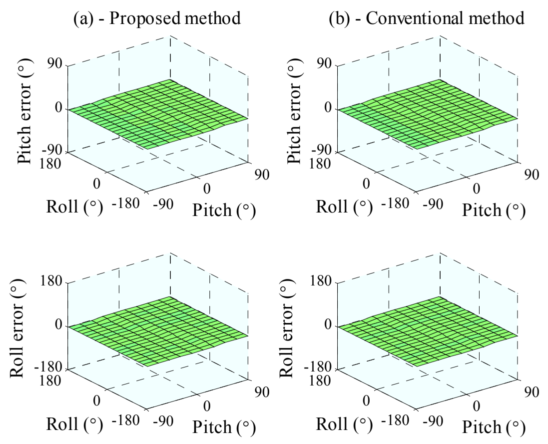

Fig. 3 Simulation results in ideal condition, noise is zero, confirmed the calculation accuracy of both methods.

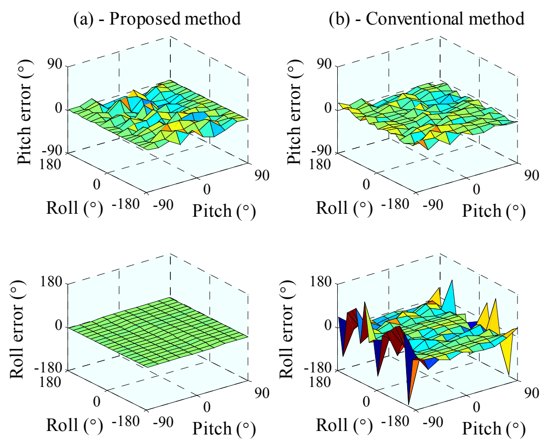

Fig. 4 Simulation results when noise intensity is nonzero. Only roll angle of the proposed method can be computed accurately. The remaining angles have large errors.

Secondly, when noise is nonzero, the simulation results are shown in Fig. 4. The errors in the roll angle of the proposed method are almost small (Fig. 4a). This means that Φ_P is still measured accurately under the effects of the external noise. On the opposite side, the errors in all remaining angles fluctuate strongly (Fig. 4b). Higher noise intensity is induced in the signals; stronger errors are generated in the computed angles. In the other words, under the influence of noise, computed values of Θ_P, Φ_C, and Θ_C may not be precise; the degradations are dependent on the noise level.

DISCUSSIONS

Both theoretical calculations and simulations prove that the proposed method can significantly reduce the effect of noise in the roll angle. Under the effects of the strong noise, the roll angle can be extracted from the output signals of the analog accelerometer. The good result can be achieved without using conventional components of the analog system such as: shielded wires, preprocessors, or filters. Therefore, the proposed method allows us to reduce the displacement space of the sensing hardware and minimize the time delay of the measurement process. Although only roll angle can be improved, this can meet the requirement of many applications. It should be noted that when the size of the hardware and/or the response speed of the software are not important, the proposed method can be combined with the above components and processes to get the better noise reduction.

The performance of the proposed method should be confirmed by experiment in a further study. Because of being mounted on a special orientation, the sensor needs to be calibrated carefully. Any misalignment could cause systematic errors in output angles. In addition, although we used the balanced lines, the small differential noise still affects the angle results. Therefore, by testing in actual condition, we can identify the problems to find out further processing steps for overcoming.

CONCLUSIONS

This paper has presented a new method for reducing the influence of the interference in roll angle measurement with analog accelerometer. The noise reduction ability is achieved by changing the sensor mounting orientation and using the new calculation formulas. The new mounting orientation is defined based on the conventional one and a special rotation matrix. The rotation matrix also converts the common equations of angle calculation to the new ones. The new equations compute the roll angle from the differential voltages among the sensor outputs. Therefore, the new method can reduce the effects of external electromagnetic noise which tends to affect the balanced conductors identically. The advantages of the proposed method have been demonstrated by simulations. The simulation results showed that under the effects of noise, the roll angle can be measured accurately, while the pitch angle has no improvement. By applying the proposed method in tilt measurement, the applicability of the analog accelerometer can be expanded by a simple way.

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NOMENCLATURE

g : standard gravity, 9.8 [m/s^2]

XYZ : conventional mounting orientation

xyz : proposed mounting orientation

g_X, g_Y, g_Z : components of gravitational vector on the XYZ frame [g]

g_x, g_y, g_z : components of gravitational vector on the xyz frame [g]

U_x, U_y, U_z : output voltages of the sensor [V]

U_{mx}, U_{my}, U_{mz} : measured voltages [V]

n : common-mode noise voltage [V]

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