Tilt Measurement System Based on Sensor Fusion with Digital Motion Processing

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Abstract. The tilt angle is a common and indispensable parameter in measurement techniques, which helps us to calculate and identify other relevant technical parameters in fields of life. The accuracy of angular measurement is a prerequisite to ensure the quality of subsequent design or operation processes. Because of its importance, many inclinometers with a myriad of measuring principles and manufacturing technologies for various purposes are incessantly being researched and made. In this paper, we propose a device that helps with measuring the inclination of the plane in both directions roll and pitch. On top of that, this prototype provides users two convenient mode including measuring the absolute value of the title angle and the relative value to a selected tilt plane. Our inclinometer is based on the application of the 6-DOF module MPU 6050 which fusing both three-axis acceleration sensor and three-axis gyroscope data to minimize errors inherent in each sensor. The finished product can be integrated into biomedical systems such as "Automated Inclining Bed" to supervise the distribution of pressure on patients' body. In addition to that, the Offset Mode also helps to adjust the beds from the current tilt to the suitable tilt for blood pressure measuring process thanks to relative tilt measurement.

Keywords: Tilt Measurement, Accelerometer, Gyroscope, Digital Motion Processing.

1 Introduction

As mentioned before, precise angular measurements play an important role in almost all areas of life. For example, an autonomous vehicle should know tilted and heading condition by monitoring and handling its own sensors to determine which order will be executed to keep it stable and keep moving [1]. Moreover, in the medical field, measuring the incline of a bed not only helps to accurately monitor blood pressure but also know the distribution of pressure on the human body [2]. In addition, intracranial pressure and extravascular vascular pressure or the distribution of water in the brain can also be diagnosed and simulated by head-down tilt [3]. On top of that, many industrial applications require accurate inclination measurement. These include platform stabilization, structural monitoring, geodetic surveying, indexing and many applications reported in researches and papers.

Therefore, there are recently many high-tech and high-precision tilt measuring devices designed for many different measurement purposes being marketed. However, the price of these devices is quite expensive. As a result, buying a good inclinometer to equip for small-scale home use or research activities of students is actually difficult. Fortunately, science is developing quickly and ceaselessly, a host of microelectronics especially microcontrollers and sensors have been studied and developed to help engineers having more materials and tools supporting for study and manufacturing process. Therefore, in this paper, we proposed a prototype of inclinometer with affordable cost and high accuracy which takes advantage of and overcomes the limitations of previous studies. Our proposed prototype uses module MPU-6050 including 3-dimensional accelerometer, 3-dimensional gyroscope and especially the Digital Motion Processor (DMP) to combine accelerometer and gyroscope data to minimize the effect of errors which are inherent in each sensor, making data processing and calibration steps with filters simpler.

This paper includes 6 sections. In addition to this section, we will analyze the theory of measurement as well as the advantages and disadvantages of our proposed sensors in section 2. Section 3 will talk about the hardware implementation. The algorithm and calibration process will be section 4. After that, the experiment result is shown in section 5. Finally, things will be wrapped up in the conclusion in section 6.

2 Proposed Sensors and Measurement Theory

In this paper, we proposed using the 6-DOF module MPU-6050 GY-521 which includes a 3-axis accelerometer, a 3-axis gyroscope and a sensor fusion called Digital Motion Processing. We will explain in more detail the structure and working principle of each component below.

2.1 Accelerometer

Accelerometers are electromechanical devices that can sense both static acceleration which is gravity of earth and dynamic forces of acceleration including vibrations and movement. Accelerometers can measure acceleration on one, two or three axes. Generally, accelerometers contain capacitive plates internally as shown in Fig.1. Some of these are fixed, while others are attached to minuscule springs that move internally as acceleration forces act upon the sensor. As these plates move in relation to each other, the capacitance between them changes. From these changes in capacitance, the acceleration can be determined [4].

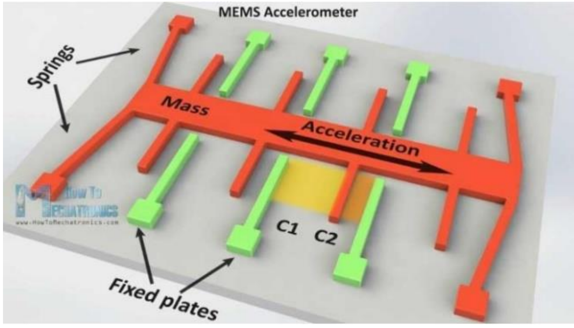

Fig. 1. Accelerometer's working principle [5].

In order to define the angles of the accelerometer in three dimensions the pitch, roll and yaw are sensed using all three outputs of the accelerometer. Pitch (ρ), roll (φ), yaw (θ) are respectively defined as the angle of the X-axis, Y-axis relative to ground and the Z-axis relative to gravity [6].

$$A_x = \frac{V_x.\mathrm{V_{ref}} - \mathrm{V_{zero}}}{\mathrm{V_{sensitivity}}} \tag{1}$$

$$A_y = \frac{V_y.\mathrm{V_{ref}} - \mathrm{V_{zero}}}{\mathrm{V_{sensitivity}}} \tag{2}$$

$$A_z = \frac{V_z.\mathrm{V_{ref}} - \mathrm{V_{zero}}}{\mathrm{V_{sensitivity}}} \tag{3}$$

$$\rho = \arctan\left(\frac{A_y}{\sqrt{{A_x}^2 + {A_z}^2}}\right) \tag{4}$$

$$\varphi = \arctan\left(\frac{A_x}{\sqrt{{A_y}^2 + {A_z}^2}}\right) \tag{5}$$

$$\theta = \arctan\left(\frac{A_x}{\sqrt{{A_y}^2 + {A_z}^2}}\right) \tag{6}$$

Where Vzero, Vref and Vsensitivity are obtained from the datasheet of the module and Vx, Vy, Vz by order are the voltage output from the X-axis, Y-axis and Z-axis of the accelerometer [6].

It is important to note that the acceleration result only provides precise orientations in static conditions, meaning that gravity is the only force acting on the sensor. In dynamic conditions such as when the vehicle is moving or when we exert force to move and rotate the sensor, the final acceleration value may be affected because the sensor cannot distinguish gravity acceleration and acceleration created by motion [7].

2.2 Gyroscope

Gyroscope is a device that measures or maintains the rotation using Coriolis effect. The gyroscope sensors use a proof mess block that vibrates in the primary direction. At the same time, this block is rotated around an axis, which causes the Coriolis force to cause it to oscillate in another direction. In this secondary direction of motion, the capacitor plate is attached to identify the capacitance change noted by this motion and thereby determine the rotation speed.

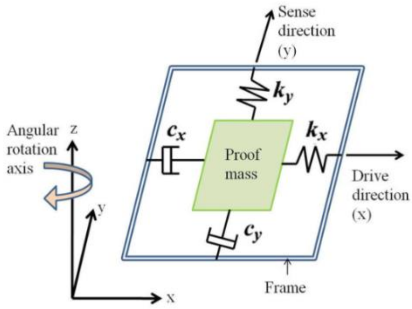

Fig. 2. Gyroscope's working principle [8].

Because the gyroscope measures angular velocity not angular orientation, to compute the orientation, we must first initialize the sensor position with a known value (possibly from the accelerometer), then measure the angular velocity (ω) around the X, Y and Z axes at measured intervals (Δt). Then multiple them together, we will have the change in angle. The new orientation angle will be the original angle plus this change. The problem with this approach is that we are integrating to find orientation which will result in small systematic errors becoming magnified over time. This is the cause of gyroscopic drift, and over long timescales the gyroscope data will become increasingly inaccurate [7].

2.3 Digital Motion Processing

As explained above, both the accelerometer and gyroscope data have methodical inaccuracies. The accelerometer provides precise outcome in the long term, but it is easily affected by noise in the initial short period of time. The gyroscope gives accurate changes in orientation in the short term, but the necessary integration leads to the drift over in output data over longer time scales. To make matter worse, using Euler angles to calculate tilt can result in Gimbal Lock, a problem occurs when two axes of the three gimbals are in a parallel configuration. Consequently, the system loses one degree of freedom and becomes a degenerate two-dimensional space [9].

The MPU6050 IMU contains a Digital Motion Processor which fuses the accelerometer and gyroscope data together to minimize the effects of errors inherent in each sensor. The DMP uses the theory of quaternions, a mathematic algorithm which helps to prevent the system from Gimbal Lock and can represent rotations over ranges of greater than 180 degrees without difficulty as well as allowing for straightforward interpolation between two quaternions, which can be useful in animation, and reducing round-off error when multiple rotation operations are performed in sequence [10].

3 Hardware Platform

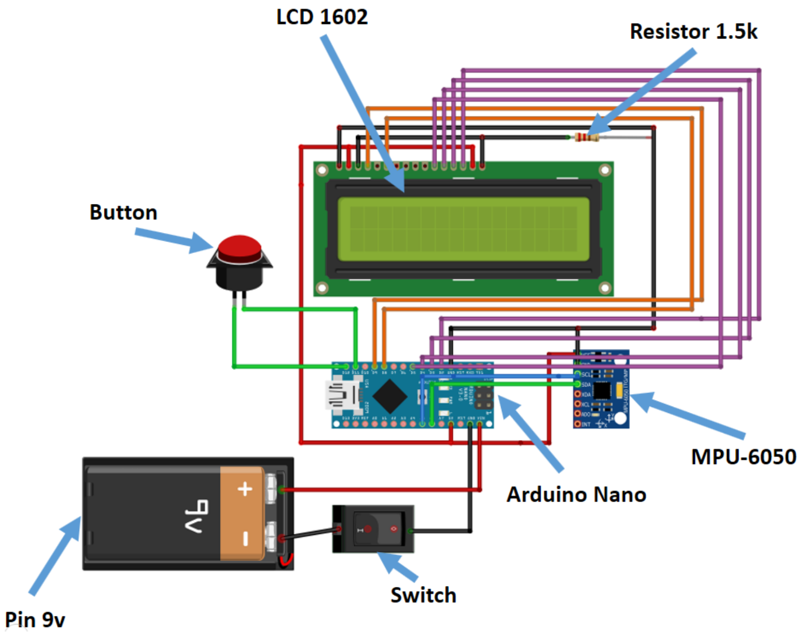

Fig. 3. The detail wiring diagram of our prototype.

In this paper, Arduino Nano which includes Atmega328 and supports 32KB Flash memory as well as 2KB SRAM is chose as the main processor. We use Arduino Nano because it has Integrated Development Environment with many available and helpful libraries, which help us save a lot of time in designing the algorithm and programming.

The inclination value is measured by the MPU-6050 module instead of just using an acceleration sensor, for example ADXL335 as in [6]. The reasons we have already mentioned in section 2.

The Arduino Nano is powered by the 9V DC battery. LCD1602 is used to display the result got from MPU-6050 module and processed by the Arduino Nano. The button helps us to change the measurement mode between Standard Mode and Compare Mode.

Arduino Nano is used to process signal and power other component by connecting them to 5V pin and GND pin of Arduino. The output of acceleration sensor MPU-6050 is connected SCL to A5, SDA to A6 of Arduino Nano.

4 Implementation and Calibration Process

4.1 Algorithm

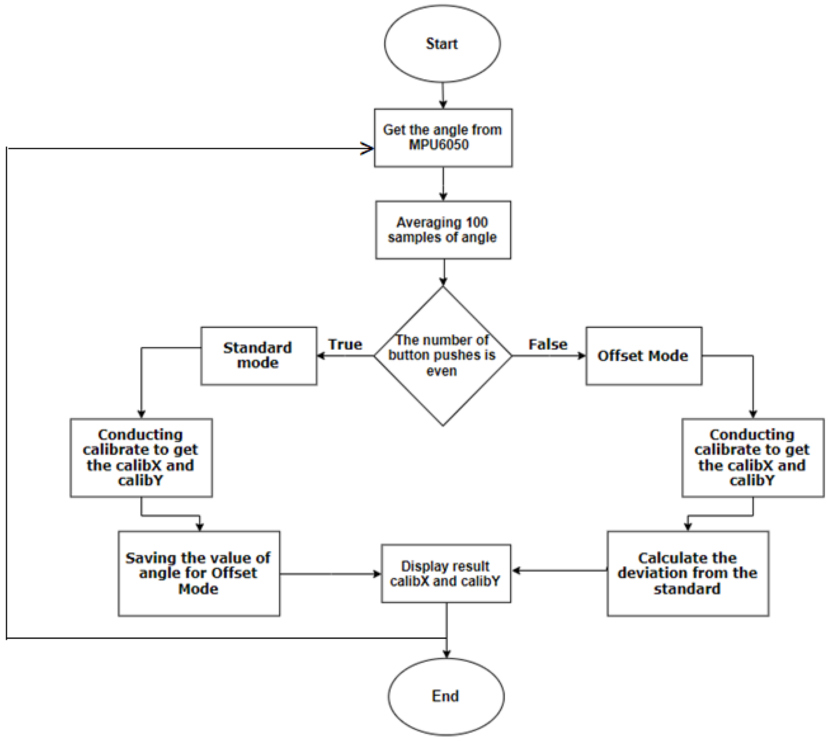

Fig. 4. Our algorithm flowchart.

The main program is reading the output voltage from the sensor, converting it into the angles of the accelerometer in three dimensions which are pitch (ρ) and roll (φ) by using the equations from eq. (1) to eq. (5) as mentioned above.

To reduce the noise, we do not take every output value as the final tilt value; instead we conduct sampling of 100 values and calculating the average of those data. This step makes the reading value steadier and more reliable. The average value then will be calibrated to reduce the systematic errors of the sensors. The calibration process is going to be presented later in this paper.

Our proposed algorithm has two working modes: Standard Mode and Offset Mode. “Standard Mode” is the normal working mode of our prototype, which returns the absolute inclination value of the angle. The “Offset Mode” is triggered by pressing the button once and this mode last until the user presses the button again. In this mode, we will save the tilt value when the user press the button as the offset value, then each time after receiving the output calibrated angle, we will subtract it from the previous offset value before showing it on the screen. Then we will get the relative angle to the selected plane.

4.2 Calibration Process

As we mentioned earlier, the output data which provides by both the accelerometer and gyroscope have some systematic errors that depend on vibration and mechanical noise. Although the output data is better with the help from DMP's algorithm, there still exist some small inaccuracies. Consequently, a calibration by finding a regression equation formula is necessary. We measured 30 different tilt angles from 0 to 90 degrees and compare the receive value to the real value of the inclination. Later, we applied several nonlinear regression methods to find the regression equation formula. Based on the data samples, we decided to divide the inclination value into 2 ranges of values which are [0, 78], (78, 90] to ensure the highest compatibility of the regression equation for each range. As a result, the regression equations from eq. (7) to eq. (10) are respectively used as formulas to calibrate tilt value of the X-axis angle and Y-axis angle in 2 different ranges:

$$y = 0.0032x^2 + 0.5537x + 1.2395 \tag{7}$$

$$y = 0.4329x^2 - 69.475x + 2857.8 \tag{8}$$

$$\mathrm{y} = 0.0023x^2 + 0.6305x \tag{9}$$

$$y = 0.1162x^2 - 16.888x + 672.69 \tag{10}$$

where, the variable y stands for the inclination value after calibration and x is the inclination value from the calculation of the MPU 6050 module.

5 Experimental Results

In order to test the accuracy of the angle meter, we carried out an experiment with some difference angles (between this device and X-axis and Y-axis). Experimental results are presented in the Table 1 below.

As we can see, the data obtained from our prototype is highly reliable. Especially, when the tilt angle is bigger than 10 degrees, the error is just about 3% or less, which is acceptable. If the angle is smaller than 10 degrees, the inaccuracy sometimes can reach 16%, which is quite big. However, it is just because the angle is too small that only a tiny deviation in degrees, which usually is smaller than 1 degree, can leads to a large percentage in number. Moreover, we rarely have to measure those small angles, so this error does not affect too much.

Nevertheless, our device still has some disadvantages. It can be affected by noise for a few seconds right after a slight vibration. So, we advise users to wait for a few seconds after changing the inclination to have stable data. To make matters worse, there can have different outputs in different places due to the change of earth's gravity. But this problem can easily be solved by an automatic calibration based on the available gravity's data of the location.

Table 1. Accuracy of our prototype.

Cellphone's tilt software	Our device X-axis	Error X (%)	Our device Y-axis	Error Y (%)
0	0.8	-	0.8	-
5	4.7	6.00	5.8	16.00
10	9.6	4.00	10.4	4.00
15	14.6	2.67	15.3	2.00
20	19.5	2.50	20.6	3.00
25	24.8	0.80	25.7	2.80
30	30.1	0.33	30.3	1.0
35	35.5	1.43	35.7	2.00
40	40.5	1.25	40.5	1.25
45	45.6	1.33	45.8	1.78
50	50.6	1.20	50.6	1.20
55	55.3	0.55	55.2	0.36
60	59.7	0.50	61	1.67
65	64	1.54	65.6	0.92
70	70.4	0.57	70.4	0.57
75	74.6	0.53	75.3	0.40
80	80.7	0.88	80.4	0.50
85	84.6	0.47	84.5	0.59
90	89.1	1.00	89.3	0.78

When compared with those inclinometers currently on the market, our proposed prototype approach stable results with high precision and high reliability. In addition to that, our device has small size and economic, competitive price which is smaller than 20$.

6 Conclusion

In this paper, we proposed a prototype for measuring tilt angle which have a host of applications in various fields. We also mentioned our main algorithm as well as the detail hardware structure. Our inclinometer uses the module MPU-6050 which not only helps to inherit the strengths as well as overcome the limitations of just using accelerometer but also make it simpler for the algorithm and programming process. With its high-precision and reliable results, mobility, power saving, compact size and especially affordable price, we believe it is a useful tool to support both general and technical works. For further improvements and investigations in the approach to the absolute accuracy of different locations, an automatic calibration should be added to adapt to the change of gravity force. There can also have some combination with other available measurement systems, which can bring new features and improve the efficiency of those systems. For example, in biomedical uses, our device can be integrated into "Automated Inclining Bed" system to monitor the pressure distribution on patient's body or adjust robotically the bed to the suitable tilt for blood pressure measuring process thanks to the relative tilt measurement. Besides, our inclinometer can be incorporated into others autonomous mechatronic structures like robots to support control process with more accurate orientation.

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