Design of tilt measuring system based on ADXL327

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Abstract. The design of tilt measuring system based on ADXL327 accelerometer was designed. This design mainly includes hardware circuit design and system software design. The hardware circuit mainly includes the minimum system, signal acquisition module, display module and power supply module. The ADXL327 accelerometer collects the tilt signal, and the signal is acquired and processed by the AD conversion. In the software part, the acquisition of angle data and the display of data are designed, and some important subroutines are given. The actual angle test method is designed in the experiment to get the results and some data are calculated. When the angle is less than 60 degrees, the accuracy of ADXL327 accelerometer is higher, and the level is 1.0.

1. Introduction
With the development of modern society, higher requirements have been put forward for tilt measuring. In the engineering that needs to control the dynamic level of the object. The old-fashioned level instrument cannot automatically track and measure the horizontal tilt angle, which makes the feedback cannot be achieved and the system's rapid leveling function cannot be realized. In order to adapt to the development of modern industry and meet the needs of engineering, it is very meaningful to study new, high precision and multifunctional level instruments. In China, the research and development of the tilt measuring system basically continues the foreign research and development mode: measuring sensor, signal processing circuit, A/D converter, micro-control processor (MCU) and LCD display.

In this paper, we design a tilt measuring system using a micro-controller [1] and an acceleration sensor. The microcontroller adopts the STC12C5A60S2, which is fully compatible with the traditional 8051 MCU. It is a fast MCU with low power consumption which 8-12 times faster than 8051. The acceleration sensor is ADI's ADXL327 accelerometer[2]. This sensor has the advantages of small size, low power consumption and low price compared with other acceleration sensors of ADI, such as ADXL1002, ADXL212, ADXL206, etc. The combination of STC12C5A60S2 MCU and ADXL327 accelerometer can make the design of tilt measuring more flexible. Moreover, the measuring results in this paper can be visually displayed on LCD12864, adding alarm and other functions to monitor some special cases.

2. Overall design
The main hardware functions of the tilt angle measuring system based on the single chip are as follows. Triaxial acceleration sensor ADXL327 collects tilt angle signals, and outputs voltage signals to A/D conversion [3] port of MCU. The MCU process analog signals. Then it outputs angle values on the LCD screen, and controls the actions of the sound-light alarm module. The general block diagram of the tilt measuring system based on MCU is shown in Fig.1.
3. Angle measuring principle

As shown in Fig.2, the X-axis rotates through gravity. Only when the X-axis of the device is always on the plane of gravity, the inclination calculation angle is accurate [4]. Because only one axis measuring is used in this method. Any rotation on other axes will reduce the magnitude of acceleration on the X-axis, and the calculation of the inclination angle will generate error.

According to the basic trigonometric identity, the projection of a gravity vector on the X-axis produces an output acceleration. Its magnitude is equal to the sine of the angle between the X-axis of the acceleration sensor and the horizontal plane. Assuming that gravity is 1g, the X-axis output acceleration is:

\[ x = 1g \times \sin \theta \]  

(1)

Which \( x \) represents the X-axis output acceleration.

When rotating through gravity, the output of the accelerometer conforms to sine relation. The inverse sine function can be used to convert acceleration into angle. The formula is as follows:

\[ \theta = \sin^{-1}\left(\frac{x}{1g}\right) \]  

(2)
When the angle of inclination changes greatly nearby ±90°, the output acceleration changes lightly. Because of this shortcoming in uniaxial measuring, the tilt measuring method introduced in this paper is biaxial measuring. Based on the X-axis, added the Y-axis, and the X-axis is perpendicular to the Y-axis. So there is one important advantage to measuring a given angle of inclination in this way: a constant sensitivity. That is, as the incremental sensitivity of an axis decreases, the incremental sensitivity of the other axis will increase. Reduce the dependency on the alignment with the gravity plane. Even if there is a tilt on the third axis, the exact value can be measured.

The method of measuring angle with two axes is similar to that of one axis. Since the Y-axis is perpendicular to the X-axis, the arcsine function of the X-axis can be calculated to obtain the angle between the X-axis and the horizontal plane. At the same time, the inverse cosine of the Y-axis was subtract from 90 degrees. Then take the average of both and get the angle value of the X-axis. It is more sensitive than single axis measuring. The formula is as follows:

\[
\theta = \{\sin^{-1}\left(\frac{x}{1g}\right) + \left[90° - \cos^{-1}\left(\frac{x}{1g}\right)\right]\} \times \frac{1}{2} \times \frac{180°}{\pi}
\] (3)

4. Software design
In the tilt angle measuring system of MCU, the function of hardware equipment is defined by software. When the system is powered on, the program in MCU is running. First, the A/D converter and LCD12864 LCD are initialized with the program. Then the system is judged whether to enter T0 interrupt. If not, wait for the interrupt to enter. If T0 interrupt is entered, A/D sampling is performed. The process is as follows. The ADXL327 sensor collects tilt data. The measured signal is transmitted to the A/D conversion port in the form of analog signal, and the analog signal is converted into digital signal. The sampling time is 2 milliseconds. If there is no arrival time, wait for sampling to end. The formula to calculate the tilt angle is programmed and displayed on the LCD12864 display screen. The alarm program for audible and visual alarm with an angle greater than 60 degrees is set. The overall flow chart of the software design is shown in Fig.3.

![Figure 3. Overall flow chart of software design](image)

The program is in the T0 interrupt. Since the output signal of the ADXL327 acceleration sensor is an analog signal, the acquisition process needs A/D conversion. The A/D conversion channel and P1 port multiplexing of STC12C5A60S2 can be set as A/D conversion in any one of the 8 channels by
software design. In this paper, only the X-axis and Y-axis of ADXL327 are used to measure the tilt angle. So there are two A/D converters needed. To be used as the port for A/D, the corresponding position 1 in the P1ASF special function register is required. The calculation formula of A/D conversion results is as follows:

\[ \text{Result} : (\text{ADC}\_\text{RES}[7:0], \text{ADC}\_\text{RESL}[1:0]) = 1024 \times \frac{V_{\text{in}}}{V_{cc}} \]  

(4)

\( V_{\text{in}} \) is the input voltage of analog input channel, namely the output voltage signal of ADXL327 acceleration sensor. \( V_{cc} \) is the actual operating voltage of the single chip microcomputer. Using the single chip operating voltage as the analog reference voltage. For the convenience of calculation, the ideal value of acceleration and gravity of X-axis output is represented in the new angle calculation formula (3).

The specific transformation is as follows: when the X-axis is in position of \(+1g\), the maximum number of X-axis A/D conversion is 442 on the display screen. When the X-axis is in position of \(-1g\), the minimum number of the X-axis A/D conversion is 247 on the displayed screen. Take the average of the maximum value and the minimum value is 344. That is, the digital output value is the position of the X-axis located of \(0g\). From \(0g\) to \(+1g\), the X-axis angle changes 90 degrees. The data measured on the X-axis is converted to digital change by A/D value from 442 to 344. The new angle formula is as follows:

\[ \theta = \{\sin^{-1}\left(\frac{x-344}{98}\right) + [90^\circ - \cos^{-1}\left(\frac{x-344}{98}\right)]\} \times \frac{1}{2} \times \frac{180}{\pi} \]  

(5)

Which \( x \) represents the output when the accelerometer is in different positions.

5. Experiment and data analysis
The test results are as follows. \( U_x \) Represents the actual angle of the X-axis away from the horizontal plane. \( U'_x \) Represents the measured angle of the X-axis. \( U_y \) Represents the actual angle of the Y-axis away from the horizontal plane. \( U'_y \) Represents the measured angle of the Y-axis. In this paper, we use the knowledge of plane geometry to measure the Y-axis inclination. As shown in Fig.4, the X-axis is always perpendicular to the Y-axis, and the actual angle of the X-axis is known. The Y-axis can be used to measure the actual angle of the X-axis to be 90 degrees minus the angle difference of the X-axis.

![Figure 4. Geometrical relationship between X-axis and Y-axis](image)

The reference voltage of A/D conversion is the power supply voltage of the MCU. According to the high probability of repeated measuring at 5.032 volts, the following table is the experimental data of the microcontroller voltage at 5.032 volts.
Table 1. First tilt measuring results (°)

| $U_X$ | $U'_X$ | $U_Y$ | $U'_Y$ |
|-------|--------|-------|--------|
| 0     | 0      | 90    | 90     |
| 15    | 15     | 75    | 74     |
| 30    | 29     | 60    | 60     |
| 45    | 45     | 45    | 44     |
| 60    | 58     | 30    | 29     |
| 75    | 70     | 15    | 19     |
| 90    | 78     | 0     | 11     |

Table 2. Second tilt measuring results (°)

| $U_X$ | $U'_X$ | $U_Y$ | $U'_Y$ |
|-------|--------|-------|--------|
| 0     | 0      | 90    | 90     |
| 15    | 14     | 75    | 75     |
| 30    | 27     | 60    | 63     |
| 45    | 44     | 45    | 45     |
| 60    | 60     | 30    | 29     |
| 75    | 71     | 15    | 18     |
| 90    | 81     | 0     | 8      |

Table 3. Third tilt measuring results (°)

| $U_X$ | $U'_X$ | $U_Y$ | $U'_Y$ |
|-------|--------|-------|--------|
| 0     | 0      | 90    | 90     |
| 15    | 15     | 75    | 74     |
| 30    | 30     | 60    | 61     |
| 45    | 46     | 45    | 44     |
| 60    | 58     | 30    | 30     |
| 75    | 71     | 15    | 18     |
| 90    | 81     | 0     | 9      |

The specific experiment is shown in the following part.

When the actual inclination angle of the X-axis from the horizontal plane is 0 degrees, the inclination angle of X-axis measured by the accelerometer is 0 degrees. The angle measured by the geometric relation of the Y-axis is 90 degrees, and the inclination angle measured by the dual-axis is 0 degrees.

When the actual inclination angle of the X-axis from the horizontal plane is 30 degrees, the inclination angle of X-axis measured by the accelerometer is 30 degrees. The angle measured by the geometric relation of the Y-axis is 59 degrees, and the inclination angle measured by the dual-axis is 30 degrees.

When the actual inclination angle of the X-axis from the horizontal plane is 75 degrees, the inclination angle of X-axis measured by the accelerometer is 75 degrees. The angle measured by the geometric relation of the Y-axis is 14 degrees, and the inclination angle measured by the dual-axis is 75 degrees.

Take the average value of the above table, and the summary Tab.4 is as follows.

The absolute error (AE), reference error (RE), fiducial error (FE) and level of the ADXL327 accelerometer are calculated from the results in Tab.4. Then the Tab.5 is obtained.

According to the error data, when the measured inclination is greater than 60 degrees, the error of ADXL327 accelerometer is relatively large. That is, when the measured inclination is less than 60
degrees, the sensitivity is relatively high. When the Angle is less than 60 degrees, the ADXL327 accelerometer is rated as 1.0.

|   |   |   |   |   |   |
|---|---|---|---|---|---|
|   |   |   |   |   |   |

Table 4. Results of tilt measuring (°)

| U_x | U'_x | U_y | U'_y | U  | U'  |
|-----|------|-----|------|----|-----|
| 0   | 0    | 90  | 90   | 0  | 0   |
| 15  | 15   | 75  | 74   | 15 | 15  |
| 30  | 29   | 60  | 60   | 30 | 29  |
| 45  | 45   | 45  | 43   | 45 | 45  |
| 60  | 59   | 30  | 31   | 60 | 59  |
| 75  | 71   | 15  | 18   | 75 | 71  |
| 90  | 80   | 0   | 8    | 90 | 80  |

Table 5. Error analysis table (°)

| U_x | U'_x | AE  | RE  | FE  |
|-----|------|-----|-----|-----|
| 0   | 0    | 0   | 0   | 0   |
| 15  | 15   | 0   | 0   | 0   |
| 30  | 29   | 1   | 3.45% | 1.11% |
| 45  | 45   | 0   | 0   | 0   |
| 60  | 59   | 0   | 1.69% | 1.11% |
| 75  | 71   | 0   | 5.63% | 4.44% |
| 90  | 80   | 10  | 12.5% | 11.1% |

6. Summarize
The design of angle measuring system based on single chip microcomputer is realized by the ADXL327 acceleration sensor. The different position of the X-axis angle are measured. Using the 10 bit A/D conversion part of the MCU named STC12C5A60S2, the analog signal from ADXL327 is converted into digital signal. The tilt measuring method introduced in this paper is biaxial measuring. So there is one important advantage to measuring a given angle of inclination in this way: a constant sensitivity. Reduce the dependency on the alignment with the gravity plane. Even if there is a tilt on the third axis, the exact value can be measured. Through the Keil software programming ultimately in LCD12864 LCD screen displays the output values of the X-axis and Y-axis.

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