Digital System for Aircraft Attitude Measurement

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Abstract

Aircraft convention defines the attitude parameters in terms of three angles: roll, pitch and heading. These angles are referenced to the local horizontal plane defined by gravity vector. Attitude information for aircraft is obtained by using spinning rotor or ring laser gyroscopes. These systems are very precise but they suffer from many problems such as high cost, large size and weight and the requirements for elaborate and intricate mechanical structure.

These problems can be reduced by the exploitation of the micromachined technology.

In this work, an attitude measuring system based on the ADXL202 accelerometer, the HMC2003 magnetic sensor and the ADuC812 microcontroller has been designed and implemented. An algorithm for decoding of the ADXL202 output signals is described and implemented as software programs written in C-language to perform and display the attitude measurements and a correction method for the errors introduced by tilt angles is described.

The measuring system operation is examined by the test of the reading's repeatability and constancy. A good repeatability and constancy with a high degree of precision and small amounts of error and dispersion are found from these tests.

الخلاصة

من المتعارف عليه أن وضع الطائرة يمكن تعريفه من خلال ثلاث زوايا هي زاوية الدحرجة، زاوية الميلان وزاوية الأنعراج حيث يكون مرجع هذه الزاويا هو المستوى الأفقي المحلي لسطح الأرض والعمودي على متجه الجاذبية الأرضية. عادة يتم قياس وضع الطائرة من خلال إستخدام الجايروات التقليدية ذات المحور الدوار أو تلك التي تستخدم تقنيات الليزر. ولكن على الرغم من دقة هذه الأجهزة إلا أنها تعاني من مشاكل عديدة مثل إرتفاع كلفتها، كبر حجمها ووزنها، وحاجتها إلى بناء ميكانيكي محكم ومعقد. هذه المشاكل يمكن تقليلها من خلال توظيف محاسن تقنيات المعدات السليكونية الدقيقة.

في هذا العمل تم تصميم وتنفيذ نظام لقياس وضع الطائرة بالأستفادة من تقنيات المعدات السليكونية الدقيقة حيث تم بناء النظام إعتماداً على مقياس التعجيل نوع ADXL202، المتحسس المغناطيسي نوع HMC2003 و المسيطر الدقيق ADuC812 . لقد تم وصف وتنفيذ طريقة مناسبة للتعامل مع خرج مقياس التعجيل لغرض زيادة سرعة قراءة المعلومات من المقياس وكذلك تم استخدام طريقة لتصحيح الأخطاء في قراءات النظام نتيجة لزوايا الميلان وتم تنفيذ هذه الطرق كبرمجيات كتبت بلغة-C لغرض إجراء عملية قياس وعرض النتائج على شاشة الكومبيوتر.

لقد تم اختبار عمل نظام القياس من خلال اختبار تكرارية وثبوتية قراءات النظام وقد تم الحصول على نتائج جيدة ظهرت من خلال الدقة العالية والمقدار القليل من الخطأ والأنحراف لقراءات نظام القياس.

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1. Introduction

Attitude information for aircraft is currently obtained by spinning rotor or ring laser gyroscopes (RLG). The display of the information to the pilot is presented mechanically by the gyros themselves. Commercial and military aircraft generally have computer-based cathode ray tube (CRT) or liquid crystal display (LCD) that are driven by inertial measuring units (IMUs). These systems are very precise but have high cost and small mean time between failure [1].

The inertial navigation system (INS) or unit (INU) is made up of a navigation computer and a set of accelerometers and gyroscopes generally called inertial sensors. The group of inertial sensors is commonly called an inertial measurement unit (IMU) or an inertial reference unit (IRU). The inertial sensors might be mounted in a set of gimbals so that they stay level and head in a fixed direction no matter how the aircraft moves. This construction is called a platform system. Alternatively, the instruments might be attached to the aircraft structure, in which case they measure its motion components in the aircraft axes set, and the system computes the direction Traveled in the reference axes by transforming the measurements from the aircraft axes to the reference axes. This construction is known as strapdown system, or in instruments jargon "strapped down" to aircraft [2].

In recent years the silicon micromachined sensor has made tremendous advancements in terms of cost and level of on-chip integration for acceleration, vibration and attitude measurements. By implementing additional bi- metal oxide semiconductor (BiMOS) circuitry on-chip, these products provide sensors and signal conditioning in a single package that requires a few external components to complete the circuit. Some manufacturers have taken this approach one step further by converting the analog output of the sensor to a digital format such as duty cycle. Because of these advances, the micromachined technology is finding its way into a large area of applications [3].

2. The Attitude Measuring System

The block diagram of the designed system is shown in Fig.(1). The system measures the roll and pitch angles using the ADXL202 accelerometer, while the HMC2003 magnetic sensor was used to the heading measurements. Moreover, the ADuC812 microcontroller was used for processing the data received from the accelerometer and magnetic sensor and transmit the processed data to a personal computer.

2.1 The ADXL202 Accelerometer

The ADXl202 accelerometer has the following features [4]:

1. Two-Axis Acceleration Sensor.
2. Acceleration measurement range of ± 2 g.
3. Dynamic as well as static acceleration measurements.
4. Duty cycle output with adjustable period by a single resistor.
5. Bandwidth adjustment with a single capacitor per axis.
6. Resolution of 5 mg at 60 Hz Bandwidth.
7. Shock Survival of 1000 g.

For the purpose of this work, the ADXL202 accelerometer was used to measure the pitch and roll angles.

The period of the duty cycle modulator (DCM) output was set for both channel by a single resistor from R_{SET} to ground. The equation for the period is [4]:

$$\boldsymbol{T_2} = \frac{\boldsymbol{R_{SET}}(W)}{\boldsymbol{125\,M}W} \qquad \textbf{(1)}$$

In this work, the used resistor R_{SET} = 125 KΩ, so that T_2 = 1 ms.

2.1.1 Decoding the ADXL202 Output

In this work, an efficient method of measuring the period and duty cycle of the PWM waveforms was used. Fig.(2) shows the waveforms from X_{OUT} and Y_{OUT}. The Duty Cycle Modulator (DCM) uses the same triangle wave reference for the X and Y channels; therefore, the midpoints of the T_1 of each period are coincident, and even though the X and Y duty cycle outputs are different, the mid points of T_1 are synchronized. Thus, an improved PWM decode technique can be used to speed up the data acquisition time.

The counter is started at the rising edge of the X output (T_a = 0). The count at the falling edge of the X output (T_b) is recorded. Then the count at the rising and falling edges of the Y output (T_c and T_d) are recorded.

By looking at the points of Fig.(2), one can say that:

$$T_{1X} = T_b - T_a = T_b \qquad (2)$$

$$T_{1Y} = T_d - T_c \qquad (3)$$

$$T_{2X} = T_{2Y} = T_2 = T_e - T_a = T_f - T_g \qquad (4)$$

Since the mid points of the high states of the X and Y duty cycle signals are coincident;

$$T_2 = \left[T_d - \left(\frac{T_d - T_c}{2}\right)\right] - \left[\frac{T_b}{2}\right] \qquad (5)$$

Thus, one sample of acceleration can be acquired from both axes every two T_2 cycles and T_2 is only calculated once for both X and Y signals.

2.1.2 Calculation of the Acceleration and Tilt Outputs

Acceleration experienced by the ADXL202 accelerometer may be calculated by the following formula [5]:

$$a = (\text{Duty Cycle} - \text{Duty Cycle at Zero g}) / \text{Duty Cycle Per g} \qquad (6)$$

where,
a = the acceleration measured in g's.

As outlined in the data sheet of the ADXL202 [4], the nominal duty cycle output of the ADXL202 is 50% at zero g and the duty cycle change per g is 12.5%. Therefore, the acceleration for both directions can be calculated from the duty cycle by using the following formula [5]:

$$a = \frac{\frac{T_1}{T_2} - 0.5}{0.125} \qquad (7)$$

where,
T_1= the pulse width, and
T_2= the period.

Acceleration is a vector quantity with both a direction and magnitude. When the tilt angles are varied along the sensitive X- and Y-axes, the acceleration vectors change and the ADXL202 responds by changing the duty cycle outputs. The pitch and roll angles are defined by the following equations [4]:

$$\phi = \sin^{-1}\left(\frac{a_x}{1g}\right) \qquad (8)$$

and

$$\theta = \sin^{-1}\left(\frac{a_y}{1g}\right) \qquad (9)$$

where,
ϕ = the pitch angle.
θ = the roll angle.

a_x = the measurements of acceleration along the X-axis.
a_y = the measurements of acceleration along the Y-axis.

2.2 The HMC2003 Magnetic Sensor

The sensor is three-axis magnetic sensor from Honeywell Inc. It provides three analogue 0.5 to 4.5 volts outputs; therefore, the sensor output should be supplied to an analog-to-digital converter (ADC) to obtain digital output signal. [6].

The HMC2003 magnetic sensor has the following features:

1. Sensitivity of (1V/gauss).
2. Field resolution of (40 μ gauss).
3. Output voltage of (2.5 ± 2 volts).
4. Field range of (± 2 gauss).
5. Bandwidth of (1 KHz).
6. Operating temperature range of (-40° to 85°C).

2.2.1 Heading Angle Measurement

In order to design digital heading measuring system, the HMC2003 magnetic sensor was connected to the ADuC812 microcontroller as shown in Fig.(3). The range of the ADC of the ADuC812 is 0 to 2.5 volts; meanwhile the output of the HMC2003 is between 0.5 and 4.5 volts. Therefore, a voltage divider is used for each sensor direction in order to reduce the full range to (0.25 to 2.25 volts).

The measured magnetic field strength will be:

$$H_{ex} = \left(X_{OUT} - 1.25\right) \times 2 \text{ gauss} \quad \textbf{(10)}$$

$$H_{ey} = \left(Y_{OUT} - 1.25\right) \times 2 \text{ gauss} \quad \textbf{(11)}$$

$$H_{ez} = \left(Z_{OUT} - 1.25\right) \times 2 \text{ gauss} \quad \textbf{(12)}$$

The heading can be calculated, using the H_{ex} and H_{ey} outputs in the horizontal plane. This can be performed using the following equation [7].

$$\alpha = \tan^{-1} \frac{H_{ey}}{H_{ex}} \quad \textbf{(13)}$$

where,
α = the heading angle.
To account for the inverse tan limits, the heading calculations must account for the sign of the H_{ex} and H_{ey} readings as follows [8]:

$$\alpha\left(H_{ex} = 0, H_{ey} > 0\right) = 270^{o} \quad \textbf{(14)}$$

$$\alpha\left(H_{ex} = 0, H_{ey} < 0\right) = 90^{o} \quad \textbf{(15)}$$

$$\alpha\left(H_{ex} > 0, H_{ey} > 0\right) = 360^{o} - \left(\tan^{-1} \frac{H_{ey}}{H_{ex}}\right) \cdot \frac{180^{o}}{\pi} \quad \textbf{(16)}$$

$$\alpha\left(H_{ex} > 0, H_{ey} < 0\right) = -\left(\tan^{-1} \frac{H_{ey}}{H_{ex}}\right) \cdot \frac{180^{o}}{\pi} \quad \textbf{(17)}$$

$$\alpha\left(H_{ex} < 0\right) = 180^{o} - \left(\tan^{-1} \frac{H_{ey}}{H_{ex}}\right) \cdot \frac{180^{o}}{\pi} \quad \textbf{(18)}$$

Equations (14) to (18) are based on the convention that the heading is counted clockwise from north to the heading direction [9].

2.2.2 Roll and Pitch Compensation

Most often, the magnetic sensor is not confined to a flat and level plane. It is often hand held, attached to an aircraft. This makes it more difficult to determine the heading, since the errors introduced by the roll and pitch angles can be quite large. If the magnetic sensor is tilted by a roll angle θ and pitch angle ϕ , then the H_{ex}, H_{ey} and H_{ez} magnetic readings can be transformed to the horizontal plane ($H_{ex(comp)}$ and

$H_{ey(comp)}$) by applying the following rotational equations [8].

$$H_{ex(comp)} = H_{ex}\cos\phi + H_{ey}\sin\theta\sin\phi - H_{ez}\cos\theta\sin\phi \qquad (19)$$

$$H_{ey(comp)} = H_{ey}\cos\theta + H_{ez}\sin\theta \qquad (20)$$

Once the magnetic components are found in the horizontal plane, the heading angle can be determined by using equations (14) to (18) which can be rewritten as follows:

$$\alpha\left(H_{ex(comp)} = 0, H_{ey(comp)} > 0\right) = 270^{o} \qquad (21)$$

$$\alpha\left(H_{ex(comp)} = 0, H_{ey(comp)} < 0\right) = 90^{o} \qquad (22)$$

$$\alpha\left(H_{ex(comp)} > 0, H_{ey(comp)} > 0\right) = 360^{o} - \left(\tan^{-1}\frac{H_{ey(comp)}}{H_{ex(comp)}}\right)\cdot\frac{180^{o}}{\pi} \qquad (23)$$

$$\alpha\left(H_{ex(comp)} > 0, H_{ey(comp)} < 0\right) = -\left(\tan^{-1}\frac{H_{ey(comp)}}{H_{ex(comp)}}\right)\cdot\frac{180^{o}}{\pi} \qquad (24)$$

$$\alpha\left(H_{ex(comp)} < 0\right) = 180^{o} - \left(\tan^{-1}\frac{H_{ey(comp)}}{H_{ex(comp)}}\right)\cdot\frac{180^{o}}{\pi} \qquad (25)$$

2.3 The ADuC812 Microcontroller

The ADuC812 is a fully integrated 12-bit data acquisition system incorporating a high performance self-calibrating multi-channel ADC, dual DAC and programmable 8-bit 8052 based MCU (8051 instruction set compatible) on a single chip [10]. The size of the counter on the microcontroller must be known to prevent an overflow. In this work, the 8052 microcontroller was clocked at 12MHz resulting in a 1MHz timer frequency

3. The Attitude Measuring System Operation

The system measures the roll, pitch and heading angles and transmits them via the microcontroller RS-232 serial port at a baud rate of 9600 bit/s. The complete circuit diagram of the system is shown in Fig.(3).

Two software programs were written to complete the operation of the system. The first program was for the measurements and driving the microcontroller, while the second was used to display the measurements on the personal computer.

3.1 Measurements and Microcontroller Driving Program

This program is written in C-language to initialize and drive the microcontroller and perform the roll, pitch and heading measurements. The program was compiled to get Intel Hex fit using keil C-51 compiler. This Hex fit was then loaded to the microcontroller using the Analog Devices Windows Serial Downloader (WSD) program.

The algorithm of the program is listed as follows:

1. Initialization: In this part the following initialization steps are performed:

a. Set the serial port to work at a baud rate of 9600 bit/s using Timer 2.

b. Set the ADC to work as interrupt driven using Timer 1.

c. Set Timer 0 to work as 16-bit timer.

2. Roll and Pitch Angles Measurement: in this part the following steps are performed:

a. On the positive going of the ADXL202 $X_{OUT,}$ start timer 0. Let $T_a = 0$.

b. On the negative going of the X_{OUT}, record the time T_b.

c. On the positive going of the Y_{OUT}, record the time T_c.

d. On the negative going of the Y_{OUT}, record the time T_d.

e. Reset Timer 0.

f. Calculate T_{1X}, T_{1Y} and T_2 using equations (2), (3) and (5).

g. Calculate the pitch and roll angles using equations (7), (8) and (9).

3. Heading Angle Measurement: The following steps are carried out:

a. Read X_{OUT} using ADC 0.

b. Read Y_{OUT} using ADC 1.

c. Read Z_{OUT} using ADC 2.

d. Calculate H_{ex}, H_{ey} and H_{ez} using equations (10), (11) and (12).

e. Read roll and pitch angles (from part 2).

f. Compensate heading measurements for tilt using equations (19) and (20).

g. Using equations (21) to (25), calculate the compensated heading angle.

4. Communication: In this part, the following steps will be performed:

a. Arrange the roll angle into two bytes to take the form R_{HB} and R_{LB}.

b. Arrange the pitch angle as P_{HB} and P_{LB}.

c. Arrange the yaw as Y_{HB} and Y_{LB}.

d. Transmit the six bytes using the microcontroller RS-232.

e. Go to part 2.

3.2 Attitude Angles Display Program

A software program is written in C-language to display the measured angles on the personal computer. The roll, pitch and heading angles are measured and transmitted via the microcontroller RS-232 serial port to the PC at baud rate of 9600 bit/s.

The data packet consists of 2 bytes (LSB and MSB) for each of the measured angle. All data are configured into 16-bit data word as follows:

$$\textbf{Measured Angle} = \textbf{MSB} \times 256 + \textbf{LSB} \qquad (26)$$

4. Test Results

The function of the attitude measuring system that is designed in this work is to measure and indicate roll, pitch and heading information.

Two types of tests were accomplished to examine and explain the operation of the designed attitude measuring system. In the first, the system reading repeatability was examined while the reading constancy was examined in the second type of test. The readings precision, the dispersion and the absolute error are calculated for each test.

4.1 Roll and Pitch Angles Measurements

The roll and pitch information, which were obtained from the attitude measuring system tests to illustrate the roll and pitch measurements are depicted in Fig. (4). The designed attitude measuring system has the ability of measuring angles from –70 to +70 degrees on the roll axis and from – 180 to +180 degrees on the pitch axis.

4.2 Heading Angle Measurements

Fig. (5) depicts the results of the tests taken to measure and demonstrate the heading information. The system is capable of measuring angles from 0 to 360 degrees on the heading axis.

4.3 Readings Repeatability Test

In this test, the repeatability of the attitude measuring system readings was examined. The test is carried out by positioning the measuring system at a certain attitude so that it indicates a certain pitch, roll and heading angles. These angles are recorded, and then the attitude of the measuring system is frequently changed and return back to the original case and the system readings are recorded for each angle. The test information is summarized in table (1).

From this test, we can conclude that a good repeatability and a high degree of precision are achieved for the measured angles except for some readings where the precision is slightly decreasing because of the fact that the measuring system is not completely return back to the original attitude. Also, small amounts of dispersion and absolute errors are found for these measurements which confirm a good accuracy and repeatability are obtained from the attitude measuring system readings.

4.4 Readings Constancy Test

In this test, the measuring system was fixed at a certain attitude for a period of four hours so that it indicates a certain pitch, roll and heading angles. The reading of these angles was recorded every fifteen minutes. The information of this test is summarized in table (2).

From this test we can conclude that the measuring system readings have a good constancy and there is no drift in reading over a long period of time with a high degrees of precision are achieved

5. Conclusions

A strapdown attitude measuring system based on the ADXL202 accelerometer, the HMC2003 magnetic sensor and the ADuC812 microcontroller has been designed and implemented. The measuring system operation is examined by the test of the reading's repeatability and constancy. A good repeatability and constancy with a high degree of precision and small amounts of error and dispersion are obtained from these tests. The low cost, light weight, small size, and the high accuracy are the main advantages of the designed attitude measuring system. An improved PWM decoding technique of the ADXL202 output signals is used to speed up the data acquisition time. A correction method implying the canceling of tilt effect on magnetic sensor output measurements is used to improve the accuracy of the designed measuring system.

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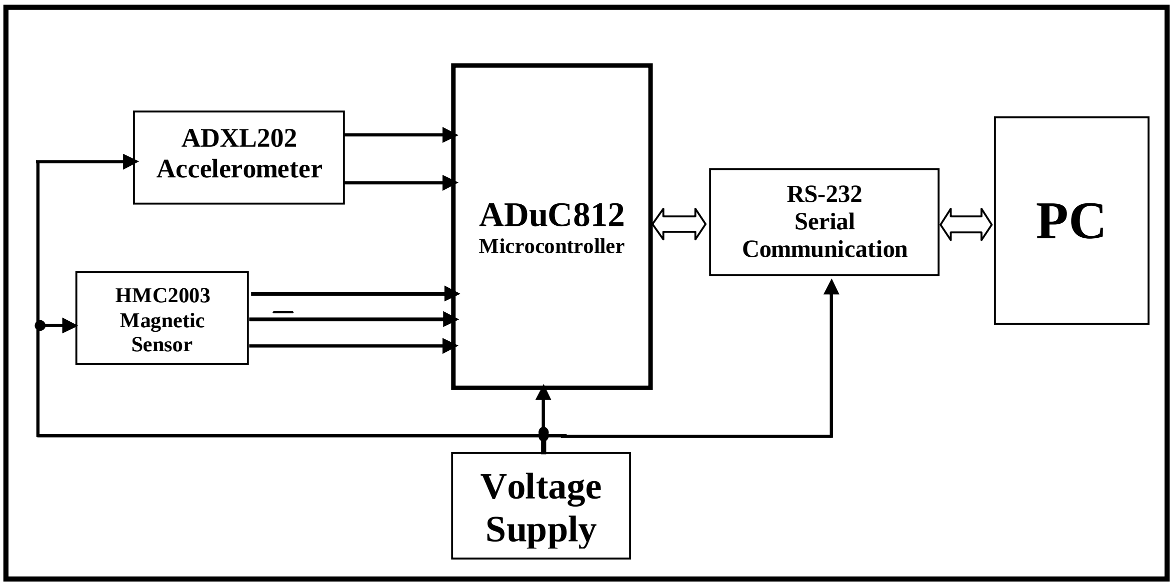

Fig.(1) Block Diagram of the Attitude Measuring System

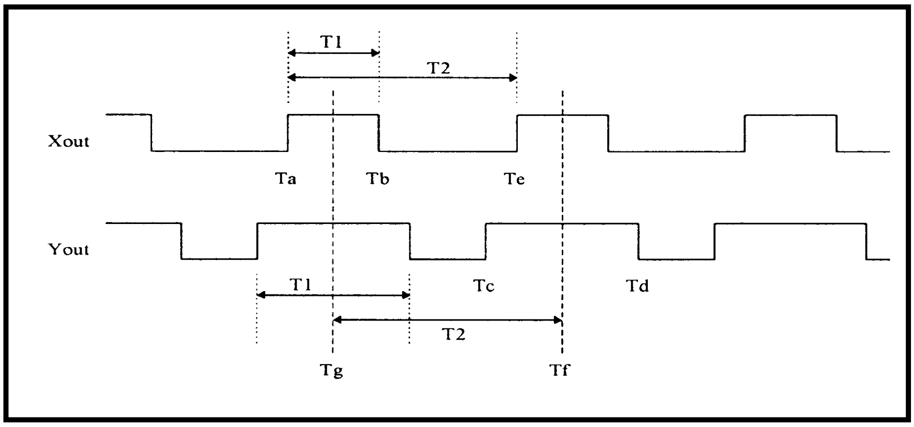

Fig.(2) High Speed Decoding Technique For The ADXL202 Output Signal.

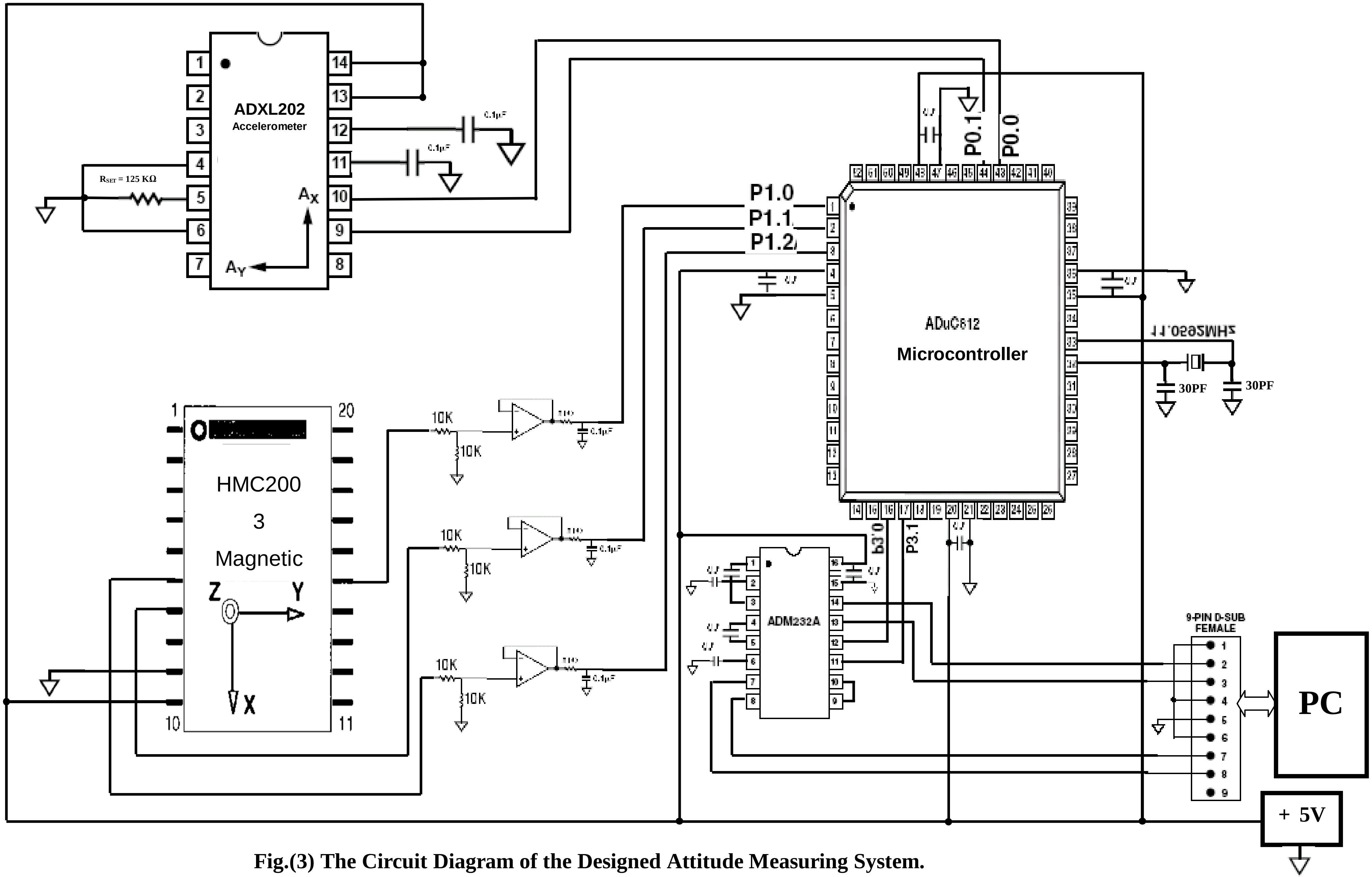

Fig.(3) The Circuit Diagram of the Designed Attitude Measuring System.

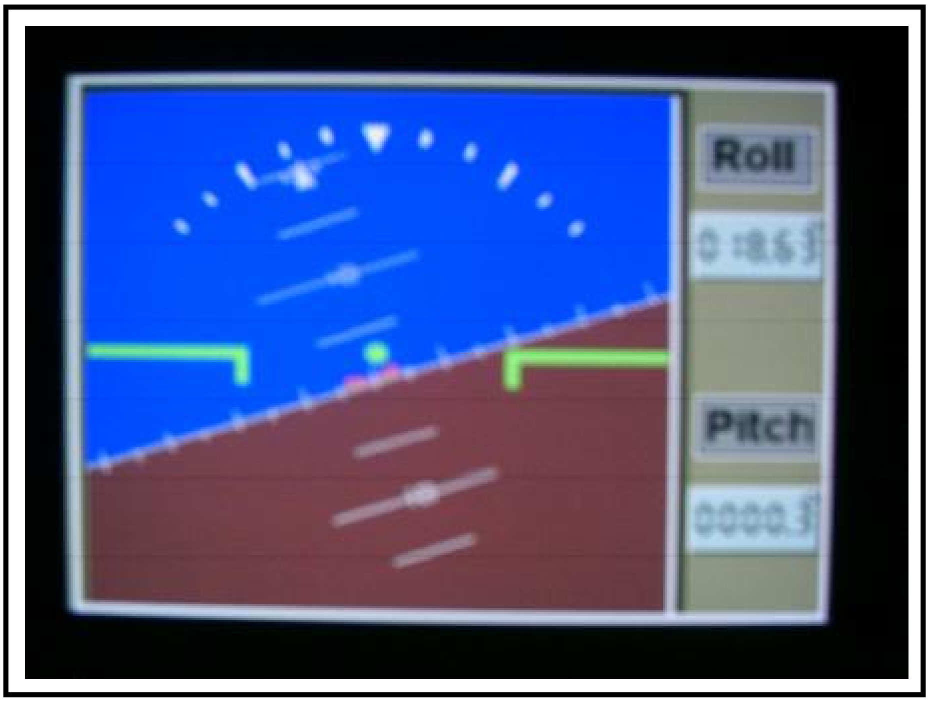

Fig.(4) Roll and Pitch Angles Measurements at 18.63 and 0.3 degrees Respectively.

Fig.(5) Heading Angle Measurement at 103.491 degree.

Table (1) Reading Repeatability Test Information

The Measured Angle	Reference (degrees)	Average Precision (%)	Dispersion (degrees)	Average Absolute Error (degrees)
Pitch	30	99.566	0.0241	0.02
	-30	99.647	0.0191	0.012
Roll	50	99.813	0.0136	0.092
	-50	99.585	0.0797	0.207
Heading	160	99.939	0.0169	0.068
	330	99.956	0.0313	0.087

Table (2) Reading Constancy Test Information

The Measured Angle	Reference (degrees)	Average Precision (%)	Dispersion (degrees)	Average Absolute Error (degrees)
Pitch	16.2	100	0.0	0.0
Roll	50.46	99.987	0.000051	0.005
Heading	90.048	99.998	0.000004	0.0015