Application of an Inertial Navigation System to the Quad-rotor UAV using MEMS Sensors

Tin Thet Nwe, Than Htike, Khine Myint Mon, Dr.Zaw Min Naing and Dr.Yin Mon Myint

***Abstract*—Inertial navigation systems are used in many situations where the use of an external reference to measure position is impractical or unreliable. Typical inertial navigation systems used in aeronautics and marine applications are highly advanced pieces of equipment costing thousands of dollars. However, inexpensive accelerometers and angular rate sensors (gyros) can be used to make a far less accurate inertial navigation unit for around $100. The design implemented in this report uses one Analog Devices MEMS rate gyro, two dual-axis MEMS accelerometers, and a Microchip PIC 8-bit microcontroller. Proper calibration is explored as a means of improving the system accuracy, as the parameters of the sensors used are not as stable or as closely specified as their more advanced counterparts.**

***Keywords*—**Inertial navigation system, low cost sensors, calibration and system design.

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) are crafts capable of flight without an onboard pilot. They can be controlled remotely by an operator, or can be controlled autonomously via preprogrammed flight paths. Such aircraft have already been implemented by the military for recognizance flights. Further use for UAVs by the military, specifically as tools for search and rescue operations, warrant continued development of UAV technology.

A quad-rotor helicopter is an aircraft whose lift is generated by four rotors. Control of such a craft is accomplished by varying the speeds of the four motors relative to each other. Quad-rotor crafts naturally demand a sophisticated control system in order to allow for balanced flight. Uncontrolled flight of a quad-rotor would be virtually impossible by one operator, as the dynamics of such a system demand constant adjustment of four motors simultaneously.

The goal of our project was to design and construct the inertial navigation system for the quad-rotor aircraft. This paper emphasizes the inertial navigation system using these MEMS (micro-electro-mechanical-systems) low-cost sensors.

II. INERTIAL NAVIGATION SYSTEM

An inertial navigation system (INS) uses inertial sensors that can measure their own movement and are completely passive, meaning that they require no external interaction to operate. They have an advantage over other sensors because they are not affected by external factors, such as friction, interference or position: “inertial sensors are desirable for general motion sensing because they operate regardless of external references, friction, winds, directions, and dimensions.

Inertial sensors have been used in aircraft and navigation systems for a long time. It is not until recently that new technology has caused the price and size of gyroscopes and accelerometers to make them available in consumer electronics. Of particular importance is the MEMS technology that has allowed small, cheap and robust sensors to enter the market.

Accelerometers measure the transactional force encountered due to their acceleration. To convert this to a velocity this output would need to be integrated once and to convert this to a position, integrated twice.

Gyroscopes measure the angular velocity that they are rotated at and to determine their angular position would require a single integration.

In the project, a single-axis gyroscope and two dual-axis tilt accelerometers are used. The former is mounted in the center of the craft in order to measure the yaw rate while in flight. The latter is mounted on the central hub of the craft. These tilt sensors each provided X- and Y- analog output signals. The outputs from the two sensors were averaged for higher sensitivity.

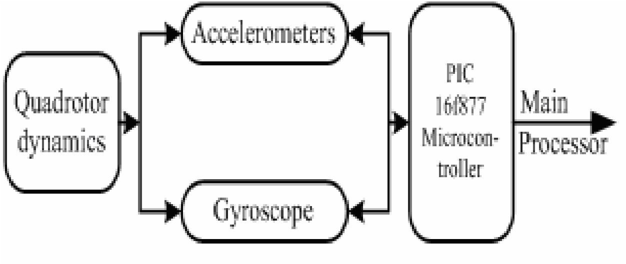

Fig. 1 Inertial Navigation System for the Quad-rotor UAV

Manuscript received November 15, 2007. This work was supported in part by the Ministry of Science and Technology, Union of Myanmar.

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III. HARDWARE CONFIGURATION

The following is a brief overview of the inertial system parts used in this navigation system.

A. MEMS Accelerometer (ADXL202)

The ADXL202 accelerometer is a solid-state accelerometer in an integrated-circuit package. The device is delivered as a 8-lead LCC (leadless chip carrier). Its dimensions are 10x9.9x5.5mm. It uses polysilicon springs to suspend a surface machined polysilicon structure over a silicon wafer. A differential capacitor measures the deflection of the structure. This is translated by signal conditioning circuitry into a duty-cycle modulated signal, which is easy to decode by a timer on a micro-controller. The accelerometer measures acceleration in two axes. This means that acceleration perpendicular to the plane defined by the axes cannot be detected. To measure acceleration in three dimensions, additional two-axis accelerometers, mounted at an angle to each other, can be used.

The accelerometer can detect accelerations in the range of ± 2g. The acceleration is expressed as a ratio between two times, T1 and T2, where T1 represents a pulse of positive voltage. (See Fig. 2.4). When the ratio T1=T2 is 0.5, the acceleration is nominally 0g.

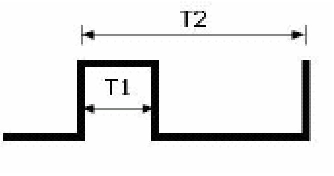

Fig. 2 Pulse width modulated output

As the acceleration range is ±2g, the span is 4g. This implies that the acceleration in units of g can be deduced by measuring the length of T1, the length of T2, and applying the following formula.

$$acceleration = \left(\frac{(T_1/T_2) - 0.5}{0.125} \right) = 8\left(\frac{T_1}{T_2} \right) - 4 \qquad (1)$$

The accelerometer gets its power supply through pins 13 and 14. Pin 5 is connected to a resistor, RSET (shown as R22 in Figure 2.2), which governs the base duty cycle period T2. The formula for this is:

$$T_2 = \frac{R_{SET}(\Omega)}{125M\Omega} \qquad (2)$$

The XFILT and YFILT pins (numbers 11 and 12) are used for setting the analog filter bandwidth of the pins. This affects the resolution capability of the accelerometer, as well as how much noise there is in the signal.

The output pins (and Y_{out}) supply the PWM output to the microcontroller. As the output is digital, i.e. one or zero, it can be input directly to the PIC and its width measured with the PIC's counter routines.

B. MEMS Gyroscope (ADXRS150)

An ADXRS150 gyroscope from Analog Devices is used and capable of measuring +/-150 degrees per second of angular velocity. First this device is small, consumes a minimal amount of current and was available in the lab. The following lines deal with electronic output characteristics. Figure 51 shows how this sensor's output behaves.

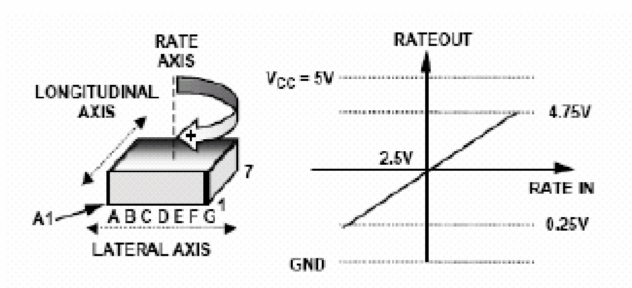

Fig. 3 Theoretical output of the gyroscope

The output signal is a voltage proportional to the rate of rotation about the axis normal to the top surface of the chip. The signal changes approximately at 12.5mV per degree of turn per. Regular sampling of this voltage signal was required to detect the rate of rotation of the module. The rate is then integrated to obtain the angle rotated between each sampling period. The gyroscope is located at the center of the structure, in order to have the best reading possible of the yaw.

C. Microcontroller

Processing data, sending and receiving information requires microcontroller. In this report, the PIC16f877A is selected to decode the signals from the accelerometers and gyroscope. This microcontroller has 8k x 14 words of flash program memory, 368 x 8 byte of data memory and 256x 8 bytes of EEPROM data memory. The PIC does not have an operating system, but simply runs the program in its memory when it is turned on.

The useful hardware features used in the system are an analog to digital converter (ADC), interrupts, timers, and capture/compare/pulse width modulation (CCP) channels. In this case, a micro-controller takes PWM inputs and analog inputs from the accelerometers and the gyroscope, decodes them into acceleration and angular velocity, and sends these values to the main onboard processor for use in the user interface. This can be done quickly, cheaply, and at low power.

D. Explanation the Interfacing Circuits

The circuitry shown in Fig. 4 is intended to demonstrate how the PIC can be used to read the input signals from the inertial sensors. The RB1, RB2, RB3 and RB4 of the PIC are connected to the XOUTs and YOUTs of the accelerometers. The RA0 of the PIC is connected to the rate output the gyroscope. In order to get the more accurate digital values from the ADC of the PIC, the RA3 is used as the voltage reference input through the zener diode.

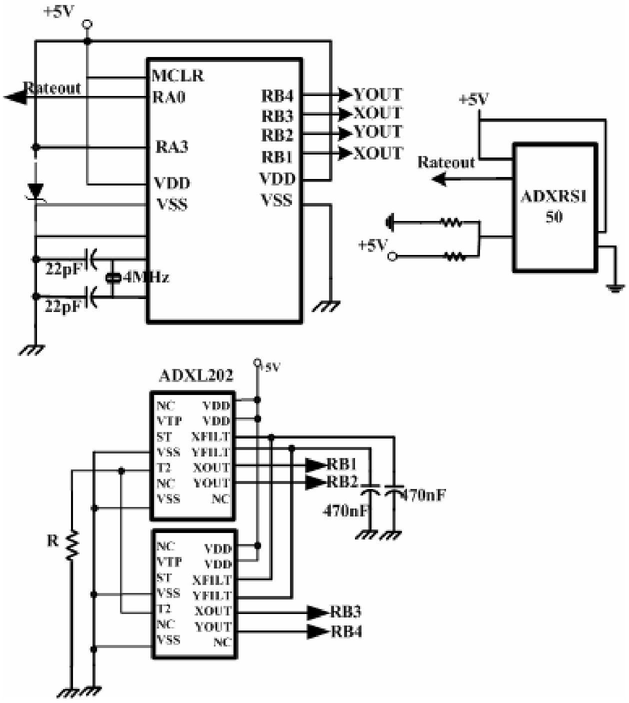

Fig. 4 The sensors interfacing circuit

IV. SOFTWARE IMPLEMENTATION

A. Gyroscope and A/D Converter

The 10 bit ADC was used to convert the output voltage from the gyroscope that represents angular velocity to an integer between 0 and 1023. The readings for each individual gyroscope were then averaged in the main control loop, which is executed every 20 times. When the results for each gyroscope are averaged in the control loop, the variables that store the sum and the number of the gyroscope readings are reset to zero so the variables will be ready for the next iteration of the control loop.

B. Determining the Angular Rate

The angular rate is obtained using the following equation:

$$Angular\_velocity = \frac{(5/1023)(A\_reading - B\_reading)}{0.0125} \quad (3)$$

The value of the gyroscope reading (B_reading) when there is zero angular velocity is subtracted from the average gyroscope reading (A_reading) that was just calculated. This difference in gyroscope readings is multiplied by 5 (the output from the gyroscope is 0-5 volts) and divided by 1023 (the A/D conversion is 10 bit so the range of the result is 0–1023). This number is then divided by 0.0125 because the gyroscope output signal changes by 12.5 milliVolts for a change in angular velocity of one degree per second.

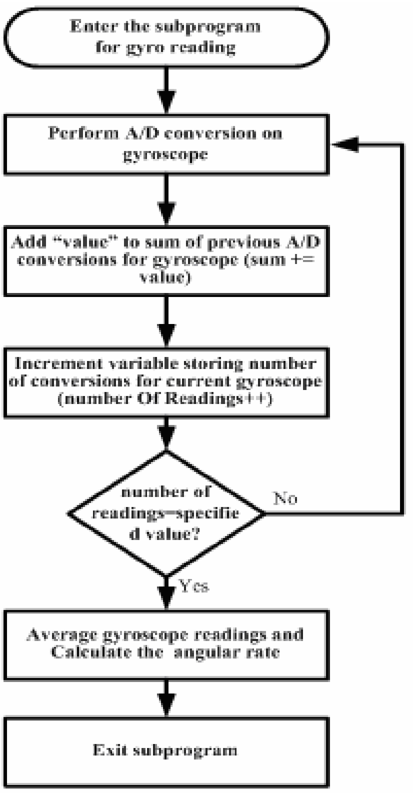

Fig. 5 Flowchart showing the calculation of the gyro output

C. Decoding the Data from the Accelerometer

The accelerometer produces a square wave, where the pulse length is proportional to the acceleration sensed on that axis. Figure 2 seen below shows an example ADXL202 output waveform. The square waves are symmetrical about their time mid-point. Therefore, T2 can be measured from midpoint to midpoint of the output square wave.

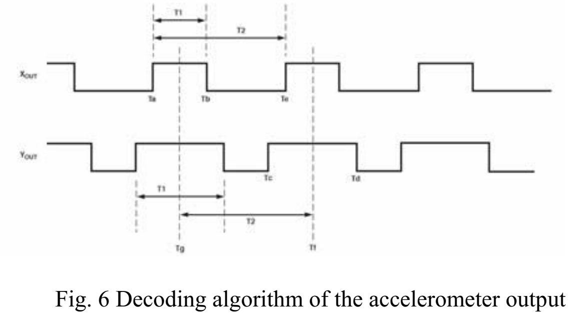

Fig. 6 Decoding algorithm of the accelerometer output

The algorithm used in the system is as follow:

1. Start the timer at the rising edge, T_a of the X channel.
2. Stop the timer at the falling edge, T_b. By definition, T_{1x} is now equal to $T_b - T_a$.
3. Repeat the process for the Y channel, and get $T_{1y} = T_d - T_c$.
4. As $T_{2x} = T_{2y}$, we get $T_e - T_a = T_g - T_f$, and after substitution

$$T_2 = T_d - \frac{T_d - T_c}{2} - \frac{T_b}{2} \quad (4)$$

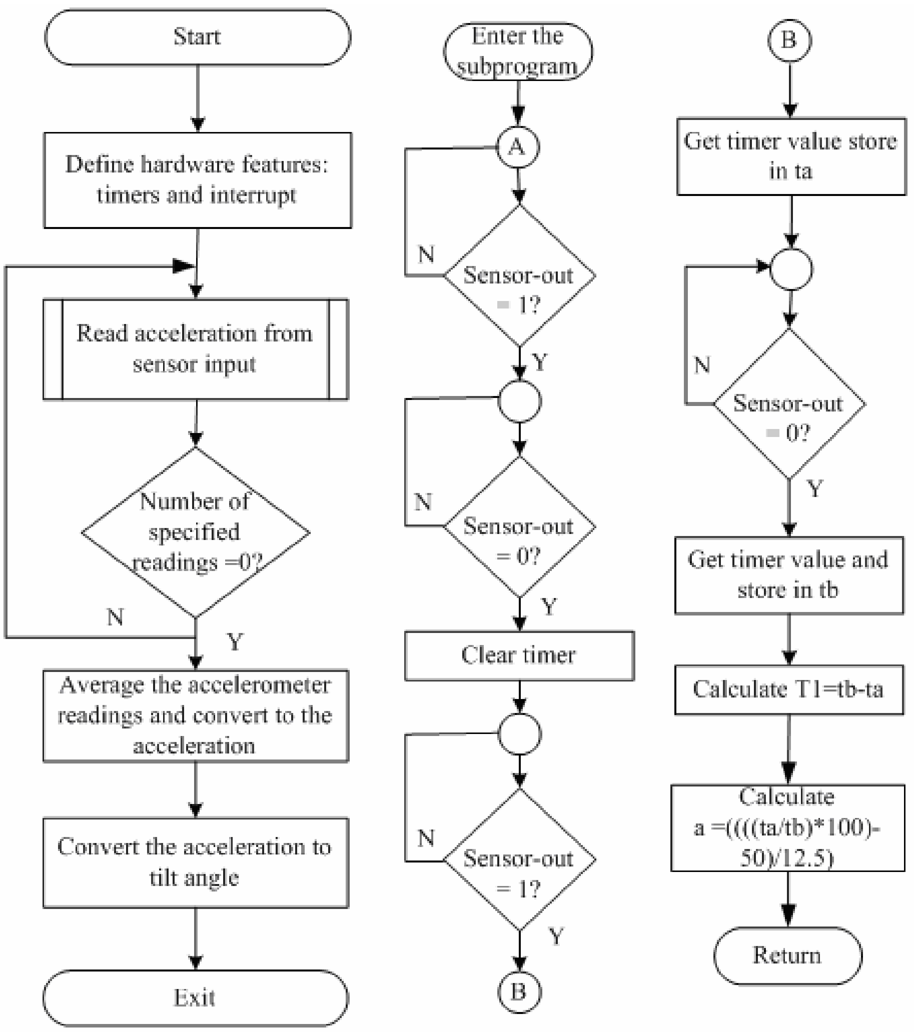

Fig. 7 Flowchart describing the accelerometer output reading

D. *Accelerometer and Timer module*

The output signal used in the report is a pulse width modulated (PWM) signal. To time the pulse length, the timer1 of the PIC 16f877A is used. The flow chart showing the reading the signal from the accelerometer is described in Fig.

As shown in the flowchart, the PIC waits until the digital signal is high in order to get accuracy of measuring the period of the pulse length. This flow chart shows the sensing algorithm for one channel of the accelerometer. By changing the input pin of the PIC, the reading of the next channel can be done following the above steps.

E. *Determing the tilt angles*

The accelerometer uses the force of gravity as an input vector to determine orientation of an object in space. The amount of the static acceleration due to gravity can be calculated as following.

$$\text{Acceleration} = \{(T1/T2) - 0.5\} / \{0.125\} \text{ (in unit g)} \qquad (5)$$

Where, 0.5 means 50% duty cycle and 0.125 means the sensitivity.

The tilt angle can be calculated using the following equation.

$$\theta = \text{asin} (\text{Acceleration in g} / 1\text{g}) \qquad (6)$$

F. Inexpensive Calibration for the accelerometers

Calibration is an important issue in sensor based systems as it is the only way to ensure a predictable quality of delivered information. The method used in this paper is the rotational calibration and it determines the offset and the scale factor for each axis separately. Hereby, an axis (e.g. the x-axis) of the acceleration sensor is oriented to the earth's gravity centre and kept stationary. It is exposed to 1g and rotated and exposed to -1g. The measured values (in g) in both positions are $U_{max,x}$ and $U_{min,x}$. Solving the equation system will result in the offset o_x and scale factor s_x for this axis:

$$O_x = \frac{U_{\max,x} + U_{\min,x}}{2} \qquad (7)$$

$$S_x = \frac{U_{\max,x} - U_{\min,x}}{2} \tag{8}$$

In order to find $U_{max,x}$ and $U_{min,x}$, the rotation has to be carried out very slowly to minimize the effect of dynamic acceleration components. The accuracy of the method relies significantly on the accuracy of the alignment.

VI. DISCUSSION AND CONCLUSIONS

The navigation system for the quad-rotor aircraft has been designed with an emphasis on using inexpensive commercially available components. These components have been integrated with a custom-designed circuit board and software has been developed to interface these components with a microcontroller.

The hardware and software used for this system can easily be integrated with additional sensors such as cameras, sonar and optic flow sensors that will allow the level of quad-rotor autonomy to be increased. In addition to the integration of more sensors, future projects can also implement more advanced control schemes, including sensor data fusion and state estimation methods, on the system.

ACKNOWLEDGEMENT

I would wish to acknowledge the many colleagues at Mandalay Technological University who have contributed to the development of this paper. I am especially indebted to the head of the electronic engineering department and my supervisor Dr.Yin Mon Myint. In particular, I would like to thank my parents for their complete support.

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