Design of a MEMS-Based Flight Information Measurement Unit  
For UAV Application

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Abstract
This paper summarizes the development of a MEMS-based flight information system. It includes an inertial and air data measurement unit and an electronic compass unit. The inertial and air data measurement unit provides the capability for three-axis accelerations, three-axis angular rates, airspeed, altitude, temperature, and angle of attack measurements. The compass system is used to measure the magnitude of the external magnetic fields. A Microchip PIC micro-controller is used in each measuring unit to perform data acquisition and deduction and to transfer the results to the host system for further analysis and processing. The inertial and air data measurement unit uses the RS232 serial port to interface with the host system while the compass unit uses the USB bus. The performance of the designed system is evaluated using an in-house designed four-axis motion platform. A specially designed wireless transmission system is also developed and integrated into the test system to improve the efficiency and flexibility of the test system. A hardware-software integrated, function tested real system is accomplished in this design.

Keywords: flight information, inertial measurement, electronic compass, motion platform, MEMs sensor

INTRODUCTION
MEMS sensors are widely used in commercial and industrial applications. For instance, MEMS accelerometers are broadly used in mobile industry (airbag deployment in collisions) and consumer electronic devices such as game controller, personal media players, notebooks (for vibration compensation in hard disk drive, Obeo (2000)), and digital cameras (for vibration reduction system compensation for image blur, Nikon Corporation (2008)). It can further be incorporated with wireless transmission technologies to provide multifunction applications.

The low cost, small size, and low power consumption features of the MEMS sensors are extremely attractive to the aviation community, especially to the navigation system designers. However, the performance features (accuracy, resolution, etc.) of the MEMS accelerometers and gyros are not good enough to satisfy the navigation demands. Therefore, the MEMS-based IMU are usually integrated with the GPS system to form a complementary scheme to provide reliable navigation information. Varieties of Kalman filters are commonly used for GPS/IMU integration (Bijker and Steyn (2008), Sergio de La Parra and Javier Angel (2005), Wendel et al. (2006), Yu et al. (2006)). The accelerations (longitudinal, lateral, and vertical) and body rates (pitch rate, roll rate, and yaw rate) measured from the MEMS IMU are used to determine the vehicle’s position and attitude. Furthermore, a MEMS-based electronic compass unit can be integrated into the system to provide the heading information.

In this paper, we also integrate the air data function to a low cost MEMS-based flight information measurement unit (FIMU). The FIMU is able to measure three axes accelerations, three axes angular rates, three axes magnetic field, static pressure (for altitude computation), two differential pressures (for airspeed computation and angle of attack determination), and temperature signals. In addition to the development of the FIMU system, a four-axis motion platform is also designed to support the functional evaluation of the MEMS-based FIMU system. To avoid tangling the power cord of the test unit and limiting the movement range of the platform, a wireless transmission unit is also developed to help data gathering.

SYSTEM OVERVIEW
The main function of the FIMU system is to measure the required signals for navigation computation and estimation including the accelerations, angular rates, magnetic fields, differential pressures, static pressure, and temperature in a real-time and continuous manner, so that the receiver (an on-board computer) can use these information to calculate the vehicle’s attitude, heading, airspeed, altitude, angle of attack and temperature information. The basic system structure is shown in Figure 1. The measured signals are sent to the receiver via a RS-232 serial interface port.
To avoid/reduce electromagnetic interference during measuring process (the magnetic sensor is extremely sensitive to its ambient disturbances), the FIMU is split into two separate units, namely, an inertial and air data measurement unit and an electronic compass unit. The inertial and air data measurement unit provides the capability for three-axis accelerations, three-axis angular rates, airspeed, altitude, temperature, and angle of attack measurements. The compass system is used to measure the magnitude of the external magnetic fields. A Microchip PIC microcontroller is used in each measuring unit to perform data acquisition and deduction and to transfer the results to the host system for further analysis and processing. The inertial and air data measurement unit uses the RS232 serial port to interface with the host system while the compass unit uses the USB bus. The performance of the acceleration and angular rate measurements are evaluated using the in-house designed four-axis motion platform. We install the inertial and air data measurement unit on the motion platform. The motion of the motion platform is controlled by a host computer. The measured data is sent to a receiver through a specially designed wireless transmission system to avoid tangling the power cord of the test unit and limiting the movement range of the platform.

Software Consideration
The primary function of the FIMU system is to perform data acquisition and deduction process. Software design for such system is common for most micro-processor based data-gathering systems. Therefore, details of the data acquisition process will not be discussed in the paper. In this section, we will only address the special considerations required for this particular unit. The key considerations that we need to pay attention to are the calibration procedures of the core MEMS sensors such as accelerometers, gyros, and magnetic sensors. The best reference for accelerometer calibration is to use the gravitational vector. When the accelerometers are mounted on the level plane (parallel to the surface of the Earth), the X and Y measuring axes are parallel to the level plane while the Z-axis is normal to the level plane. The accelerations measured on X and Y-axes are 0g; and 1g will be appears on the Z-axis. The results are measured and saved in A/D count directly. Then we flip the accelerometers so that the Z measuring axis points downwards to ground. The results are also measured and saved. After the completion of the two tests, we take the average of the results, which will be a good representation of 0g measurement. These results are used to calibrate the scaling factor of the acceleration measurement. Thus, we can predict the output value of the accelerometer at ±5g.

Calibrations for X and Y-axes are carried out in the same manner. In order to guarantee that the accelerometers are working properly, it is extremely important that self-test be performed at each time the system starts up. To initiate the self-test function, we simply switch the logic level of the self-test pin on the accelerometer from logic low to logic high. Once the self-test is engaged, an addition of 250mV will appear on the output to show that the accelerometer is functioning properly. Otherwise, a red LED is lit to show the improper function of the accelerometer. Calibration of gyro measurement is conducted using the in-house designed four-axis motion platform. Each gyro is tested for angular rate from 10 deg/sec to 150 deg/sec with an incremental of 10 deg/sec for both positive and negative direction. The results are analyzed and then used to calibrate the scaling factor of the gyro measurement. There are two self-test pins (ST1 and ST2) on the gyro that can be used to perform the self-test function. If the self-test pin ST1 is engaged (logic high), the output voltage (proportional to the angular rates) will be 0.66V below its nominal value. On the other hand, if ST2 is engaged, the output will show a 0.66V above its nominal value. A red LED will flash if it failed to pass the self-test.

The primary task for calibration of the electronic compass unit is to determine the offset value of the measurement. The simplest way is to rotate the compass unit for 360 degrees on a level plane and record the results. Then find the middle value of the measured data, which will represent the magnetic intensity of zero gauss on that measuring axis. This result is compared to the ideal value to determine the offset of the compass unit. We need to determine the offset values for all of the three axes of the compass unit. Another important point that needs to note is that we need to periodically apply set or reset to the magnetic sensor to ensure a reliable measurement. The reasons to perform a set or reset on these magnetic sensors are to recover the sensors from a strong external magnetic field that may has re-magnetized the sensor. Besides, it also can enable the sensor to perform high sensitivity measurement. Details of the set/reset function for the magnetic
sensors can be found in Honeywell Application Note AN123. Because we only need to acquire the three axes magnetic intensity signals for the electronic compass unit, we set the sampling rate to be 40Hz. That is, we will sample the external magnetic intensity every 25ms. For obtaining a reliable measurement, we generate a set pulse to the magnetic intensity every 25ms. In addition, to reduce the measuring noise, we sample every single signal five times consecutively and take the average of them to form the sampled signal at that sampling period. The measured signals are sent to the receiver through the RS232 serial data port. Therefore, the sampling rate is reduced to 20 Hz.

The structure of the motion platform is shown in Figure 2. The Z-axle drives the whole platform to rotate. The X and Y Axles are used to control the motion (attitude) of the motion platform. The U axe controls the rotation speed of the platform. The U-axis control is particularly designed for testing the performance of single axis gyros.

Figure 2. The Four-Axis Motion Platform

To avoid tangling the power cord of the test unit and limiting the movement range of the platform, a wireless transmission unit is developed to help data gathering. The core element of the wireless transmission unit is the Nordic nRF905 single-chip radio transceiver. The Microchip PIC18LF452 microcontroller is used for transmission process control, including transceiver operation mode switching, data receiving and transmitting, data inspection, and status reporting. The data transmission process is depicted in Figure 3. The IMU will periodically send the measured inertial data to the receiving terminal of the wireless transmission unit through the RS-232 serial port. The PIC microcontroller will inspect and repackage the received data, then deliver the verified data to the nRF905 radio transceiver through the SPI interface and initiate the radio transmission mode to send the data out. The nRF905 at the receiver terminal will receive and inspect the inertial data from transmission terminal and send it to the PIC microcontroller via the SPI interface. The gathered data is sent to the host computer for final inspection, decoding, data reduction and storage to complete a data transmission cycle.

Figure 3. The Wireless Transmission System

TEST PROCEDURE
The motion platform is used to verify the performance of the accelerometers. Especially, we will determine the angle and direction of inclination of the test unit from the measured acceleration signals. First, we rotate the platform around the X-axis and Y-axis for predetermined angles, and measure the acceleration signals from the test unit to compute the angle and inclination of the test unit. The computed angle and direction are compared to the predetermined ones to verify the performance of the accelerometers on the test unit.

Figure 4. Rotation of the Mounting Platform
We will use two coordinate systems in this section to describe the operation during test. One is the fixed frame system defined on the motion platform and denoted as \((f)_{X, Y, Z}\). Another one is the body frame system defined on the mounting platform and denoted as \((b)_{X, Y, Z}\). Figure 4 represents the rotation mechanism of the platform on X-Y axes. It shows that the body axes may not coincide with the fixed frame axes. When the platform rotates around \(f_X\) axis for \(\Phi\) degrees, \(b_Y\) axis on the body axes system will not coincide with \(f_Y\) axis on the fixed frame system. So, if we rotate \(f_Y\) axis, the mounting platform will rotate around the arbitrary axis \(f_Y\) instead of rotating around the \(b_Y\) axis. Rotation of \(\Phi\) and \(\theta\) degrees around \(f_X\) and \(f_Y\) axes corresponds to a rotation of \(-\Phi\) and \(-\theta\) degrees when viewing from the body frame system. Thus, the transformation matrix for rotation of the platform around \(f_X\) then \(f_Y\) and viewed from the body frame system, denoted as \(b R\), is

\[
\begin{pmatrix}
\cos \theta \\
\sin \theta \\
0
\end{pmatrix} = \begin{pmatrix}
f_X \\
f_Y \\
f_Z
\end{pmatrix}
\]

where \(R_x\) and \(R_y\) are the rotation matrices for X and Y axes respectively. The transformation matrix viewed from the fixed frame system, \(12\), is

\[
\begin{pmatrix}
\cos \phi \\
0 \\
\sin \phi
\end{pmatrix} = \begin{pmatrix}
1 \\
f_f \\
f_f
\end{pmatrix}
\]

The transformation matrix, \(21\), viewed from the fixed frame system directly for the rotation of \(\theta\) degrees around \(Y_f\) axis then rotation of \(\Phi\) degrees around \(X_f\) axis is

\[
\begin{pmatrix}
\cos \theta \\
0 \\
-\sin \theta
\end{pmatrix} = \begin{pmatrix}
R_x^{-1}(-\Phi) \\
R_y \\
R_x^{-1}(-\Phi)
\end{pmatrix}
\]

The angle of inclination of the mounting platform can be determined from computing angles between the \(Z_f\) axis of the fixed frame system and the \(Z_b\) axis of the body frame system. Figure 5 shows the situation of the two coordinate systems after the mounting platform rotates \(\theta\) degrees around \(Y_f\) axis then \(\Phi\) degrees around \(X_f\) axis. Defining \(Z_f = [0, 0, 1]^T\), then

\[
Z_b = R_y^\dagger R_x^\dagger Z_f = R_y^\dagger Z_f
\]

The angle of inclination of the mounting platform can be determined from computing angles between the \(Z_f\) axis of the fixed frame system and the \(Z_b\) axis of the body frame system. Figure 5 shows the situation of the two coordinate systems after the mounting platform rotates \(\theta\) degrees around \(Y_f\) axis then \(\Phi\) degrees around \(X_f\) axis. Defining \(Z_f = [0, 0, 1]^T\), then

\[
Z_b = R_y^\dagger R_x^\dagger Z_f = R_y^\dagger Z_f
\]

Thus, we can obtain the angle of inclination, \(i\), as

\[
i = \cos^{-1} \left( \frac{Z_b \cdot Z_f}{|Z_b||Z_f|} \right) = \cos^{-1} (\cos \phi \times \cos \theta)
\]

Let \(\mathbf{r}\) be the projection of \(Z_b\) on the \(X_f Y_f\) plane. We will use the vector \(\mathbf{r}\) to represent the direction of inclination of the \(X_b Y_b\) plane (the mounting platform). The inclination vector \(\mathbf{r}\) can be computed from

\[
\mathbf{r} = \begin{pmatrix}
\sin \theta \cos \phi \\
-\sin \phi \\
\cos \phi \\
0
\end{pmatrix}
\]

We can also use the angle, \(\gamma\), between the vector \(\mathbf{r}\) and the \(X_f\) axis to represent the inclination direction. The angle \(\gamma\) is obtained from
\[
\gamma = \cos^{-1}\left(\frac{\mathbf{r} \cdot \mathbf{X}_f}{||\mathbf{X}_f||}\right) \\
= \cos^{-1}\left(\frac{\sin\theta \cos\Phi}{\sqrt{\sin^2\theta \cos^2\Phi + \sin^2\Phi}}\right)
\]  
(7)

The coordinate system defined on the motion platform, as shown in Figure 2, is 180 degrees from the coordinate systems shown in Figure 5. Therefore, the actual inclination direction would be \(-\mathbf{r}\) as illustrated in Figure 6. Thus, the angle \(\gamma\) should be

\[
\gamma = \cos^{-1}\left(\frac{-\mathbf{r} \cdot \mathbf{X}_f}{||\mathbf{X}_f||}\right) \\
= \cos^{-1}\left(\frac{-\sin\theta \cos\Phi}{\sqrt{\sin^2\theta \cos^2\Phi + \sin^2\Phi}}\right)
\]  
(8)

The computation of the angle of inclination \(i\) (6) will not be affected by the definition of the coordinate system.

\[
\begin{bmatrix}
0 \\
\sin \theta \\
0 \\
\sin \cos \Phi
\end{bmatrix}
\]  
(11)

To test the performance of each single-axis gyro, we simply install the test unit on the mounting platform, rotate the platform for certain predetermined angular rate, and record the output from the gyro under test. Figure 7 shows the configuration for single-axis gyro test.

For three axes gyro test, we first tilt the mounting platform to a predetermined attitude through moving the \(\mathbf{X}_f\) and \(\mathbf{Y}_f\) axes as shown in Figure 8, then rotate the \(\mathbf{Z}_f\) axis to test the performance for all of the three gyros. The transformation matrix for body frame system and fixed frame system is shown in (2). So the theoretical angular rates, \(p, q, r\), (for \(\mathbf{X}_b, \mathbf{Y}_b, \mathbf{Z}_b\) respectively) measured from the gyros on the mounting platform shall be

\[
\begin{bmatrix}
p \\
q \\
r
\end{bmatrix} = R \begin{bmatrix}
0 \\
0 \\
\sin\theta \cos\theta \psi
\end{bmatrix}
\]  
(11)

The measured angular rates from the three gyros are compared to the results from (11) to verify the performance of the gyros in the design.
TEST RESULTS
In this section, we summarize the test results using the four-axis motion platform. Test configuration for gyro performance evaluation is depicted in Figure 9. The host computer controls the motion \((\Phi, \theta, \psi, \omega)\) of the motion platform. The battery powered the IMU and the wireless transmission system. The measured angular rates are sent to the receiver through the wireless transmission system.

The single axis gyro is tested for angular rate from 10 deg/sec to 150 deg/sec with an incremental of 10 deg/sec for both positive and negative direction. The test results are shown in Figure 10. The scaling factor can be represented as

\[
0.0923(R_{\text{ADC,X}}) - 192.1799 \text{ (deg/sec)} \tag{12}
\]

where \(R_{\text{ADC,X}}\) is the AD converter output for the gyro measurement (from 0 to 4096). The sensitivity of the gyro shown in Figure 10 is 13.2254 (mV/°/s). To provide a better performance, the scaling factors have to be evaluated for each gyro. For example, the scaling factors for the other two gyros (for Y and X axes) of our prototype system are

\[
0.0973(R_{\text{ADC,Y}}) - 195.1620 \text{ (deg/sec)} \tag{13}
\]

\[
0.0923(R_{\text{ADC,Z}}) - 221.4427 \text{ (deg/sec)}
\]

They are close but not exactly the same. The gyro on each of the three axes need to be aligned carefully to avoid any undesirable effects.

For three axes test, we first rotate the mounting platform around X-axis for 20 degrees then rotate around Y-axis for 20 degrees to tilt the mounting plane. Then we rotate around the Z-axis of the fixed frame system with different rotating speed and record the results from the three gyros. The results are shown in Figures 11-13. The measured data differed from the theoretical value (11) to some degree for X and Y axes measurement. But the curve fitted data still match the theoretical data quite well. The errors from this particular test condition could be gear backlash, unbalanced rotation, and vibration of the motion platform.
degrees of errors come from the motion platform. Therefore, the results show that the accelerometers actually functioning properly.

![Figure 13. Three-Axis Gyro Test: Z Gyro Results](image)

**Table 1. Comparison of the theoretical and measured angle and direction of inclination**
(numbers show in the table are in degrees)

<table>
<thead>
<tr>
<th>Angles of rotation</th>
<th>Theoretical angle and direction of inclination ([i; \gamma]) from ([5; (8)])</th>
<th>Measured and Computed angle and direction of inclination ([i; \gamma]) from ([9; (10)])</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X</strong></td>
<td><strong>Y</strong></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>[14.11; 45.44]</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>[22.27; 27.28]</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>[31.48; 19.43]</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>[22.27; 64.50]</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>[28.00; 46.78]</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>[35.53; 36.05]</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
<td>[31.48; 73.27]</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>[35.53; 59.36]</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>[41.41; 49.11]</td>
</tr>
</tbody>
</table>

To check the design of the electronic compass unit, we also use the motion platform as the test-bed. We mount the compass unit on the mounting platform and keep it in level position. Then rotate the Z-axis in steady angular rate and record the three axes magnetic intensities for a period of time. The results are shown in Figure 14. Since we rotate the X-Y plane, the measured magnetic intensities from X and Y sensors are two similar sinusoidal waves with 90 degrees differences. The results for Z axis show only small variations as expected. If we plot the X and Y results by using X results as the horizontal axis and Y results as the vertical axis, we obtain roughly a circle on the plot. We can easily determine the offset from the test results and eliminate it to obtain a calibrated set of results without offset. In this particular hardware, the offset of X-axis is 28.5 A/D count and 31.5 for Y axis. The test results with and without offset for X and Y results are shown in Figure 15. To determine the offset on the Z axis, we only need to rotate the compass unit for 90 degrees such that the Z axis of the compass unit is parallel to the level plane of the mounting platform, then redo the test as has been done for X and Y sensors. The offset on the Z sensor can be determined easily.

![Figure 14. Rotation Test for the Compass Unit on a Level Plane](image)

![Figure 15. Compass Test Results for with and without Offset](image)

Other important information that required for a successful flight is to obtain reliable air data including altitude, airspeed, temperature, and angle of attack signal. Computation of altitude, airspeed, and temperature are quite standard and familiar to the aviation community. Therefore, we will not further address these calculations in the paper. The last one that we want to bring to attention is the determination of the angle of attack of the airplane. Most of the airplane’s critical performance number is closely related to angle of attack of the airplane. The angle of...
attack signal is deduced from the measured differential pressure (the difference between the total pressure and the pressure from the angle of attack pressure port) through a pitot-tube system. Computation and determination of angle of attack signal has much more involved (including wind tunnel test and data deduction techniques) and will be reported separately.

CONCLUSION
The design of a MEMS-based flight information measurement unit system is presented in the paper. The hardware is split into two separate units. One is for inertial and air data measurement, the other is the electronic compass unit. A four-axis motion platform is also developed to support the function evaluation of the MEMS-based FIMU system. A specially designed wireless transmission system is incorporated into the test system to improve the efficiency and flexibility of the test system. Test procedures and results are also discussed in the paper. The test results verify that the designed FIMU system is functioning properly. The main purpose of the design is for UAV application. It can be easily adapted for other commercial or industrial application that require certain types of low-cost inertial, air data, or compass functions.

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REFERENCES

Honeywell Application Note AN123, SET/RESET function for magnetic sensors.


