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Design and Implementation of MARG Sensors for 3-DOF Orientation Measurement of Rigid Bodies

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Abstract:

This paper presents the latest design and implementation of the Magnetic, Angular Rate, and Gravity (MARG) sensor module. The MARG sensor module is designed for measuring 3-DOF orientations in real time without singularities. Each MARG sensor contains orthogonally mounted triads of micromachined rate sensors, accelerometers, and magnetometers for a total of nine sensor components. With an integrated microcontroller, the overall form factor is less than one cubic inch. Digital data output rate is 100 Hz. To simplify calibration procedures and filtering algorithms, it is important that the response of the individual sensor components is linear within the typical operating regions. Experiments were conducted utilizing a precision tilt table and results indicate that all the sensor components are linear. A simple hand calibration method that requires no specialized equipment is also described. It was validated by experiments that indicate hand calibration produces results that are nearly equivalent to those obtained following precision tilt table calibration.

1. Introduction

Accurate real-time tracking of orientation or attitude of rigid bodies has wide applications in robotics, aerospace, underwater vehicles, the automotive industry, virtual reality, and others. For virtual reality applications the human body can be viewed as an articulated rigid-body consisting of approximately fifteen links. If the orientation relative to a fixed reference frame can be determined for each of the links then the overall posture of the human subject can be accurately rendered and communicated.

A number of motion tracking technologies have been developed for body tracking applications, including mechanical trackers, active magnetic trackers, optical tracking systems, acoustic tracking systems, and inertial tracking systems. Most are limited by their reliance on a generated signal or a necessity for the tracked body and fixed stations positioned around a working volume to remain with in sight of one another. In either case there is a requirement to maintain some type of link over a distance. Usually, the effective range over which the link may be maintained is limited [1]. Update rates may be limited by the physical characteristics of the link used. Interference with or distortion will at best result in erroneous orientation measurements. If the link is broken, a complete loss of track will result [2, 3].

Orientation can be measured through the attachment of inertial/magnetic units containing complementary types of sensors. If averaged for a sufficiently long period, the output of an accelerometer triad can be used to measure the components of the gravity vector or the local vertical relative to the reference frame of the triad. Determination of this known vector allows correction of orientation relative to a vertical axis. Similarly, an orthogonally mounted triad of magnetometers can measure the local magnetic field vector in body coordinates. Thus, combining magnetometer data with low frequency accelerometer data provides a method for estimating the orientation of a static or slow moving rigid-body. Integration of the output of a triad of orthogonally mounted angular rate sensors is another method of estimating orientation. However, if the rate sensors are

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susceptible to noise or bias effects, errors will render these estimates useless after a short period.

In dynamic applications, a triad of rate sensors can be used as a high frequency source of orientation information and accelerometers and magnetometers can be treated as a low-frequency source of orientation information. To estimate orientation, the two sources of data can be combined together using a complementary filter [4, 5]. This technique of orientation estimation is dependent only on passive measurement of physical quantities that are directly related to the rate of rotation and orientation of a rigid body. Since no generated signals are involved, there are no range of operation restrictions. All latency in such a system is due to the computational demands of the data processing filtering algorithms and not to the physical characteristics of the generated source.

This paper describes the design and experimental testing of a magnetic, angular rate, and gravity (MARG) integrated sensor unit designed for human body tracking applications. The primary design goals were to build a reduced form factor unit capable of delivering data that would allow dynamic estimation of orientation to better than one degree accuracy. Experimental results indicate that the responses of the individual sensor components are highly linear, thus greatly simplifying calibration and software design.

2. Background

Use of angular rate sensors and accelerometers, or inertial measurement units (IMU) in land and/or underwater robots has been well documented [6, 7, 8, 9].

A study of human motion tracking using accelerometers alone was reported by Lee and Ha [10]. During motion involving small linear accelerations, a set of tri-axial accelerometers was used to determine 2-DOF rotation angles. During motions accompanied by higher accelerations, a technique is described that involves the use of two sets of tri-axial accelerometers on a single rigid-body to differentiate gravitational acceleration from motion related linear acceleration. Rehbinder and Hu [11] described an attitude estimation algorithm based on the use of angular rate sensors and accelerometers. In this case, drift in heading estimation was unavoidable due to a lack of additional complementary sensors such as magnetometers.

Hayward et al. [12] presents an attitude tracking system with GPS and inertial sensors used for aircraft. The difference between the GPS signals received by three antennas gives attitude information. Quine [13] replaces the antenna information with celestial observation data. Leader [14] describes an attitude package, which combines the outputs of inclinometers, gyros, and compasses to obtain attitude estimation. All three examples utilize Euler angles to represent orientation and a Kalman filtering algorithm to integrate the information.

Foxlin and InterSense Inc. [15] have developed and marketed an inertial/magnetic sensor called the InertiaCube. The primary application for this sensor has been head tracking [16]. Early systems utilized a fluid pendulum and three solid-state piezoelectric angular rate sensors. More recent publications indicate that the InertiaCube is capable of measuring angular rates, linear accelerations, and the local magnetic field along three axes [17]. Though filtering algorithm improvements over the years appear to have eliminated singularity and drift correction problems, the authors believe that the proprietary nature of the system and interface make using large numbers of InertiaCubes for full body tracking applications difficult.

In the spring of 2002, MicroStrain Inc. [18] announced the 3DM-G Gyro Enhanced Orientation Sensor. The sensor is based on the same components and principles described in this paper. However, the form factor of the 3DM-G sensor unit and the accuracy of the associated filtering algorithm (+/- 5 degrees) are not acceptable for full body tracking applications.

3. Sensor Design and Implementation

The MARG sensor requirements are derived from its primary intended application, that is, human body motion tracking. The sensor design goal is to develop a unit that is able to measure 3-DOF rotational motions without singularities, does not depend on a generated signal source (sourceless), and has a form factor which avoids encumbering a human subject to which the sensor units are attached. Three types of sensors are utilized to construct the MARG unit. These include angular rate sensors, accelerometers, and magnetometers.

The angular rate sensor selected for the design is the ceramic gyro CG-L43 from Tokin [19]. It is believed by the authors that this is currently the smallest rate sensor available on the market. Its dimensions are 8 × 16 × 5 mm. The manufacturer specified maximum allowable angular rate is +/−90 deg/sec. This is deemed sufficient to quicken response in human body motion tracking applications. Three of these gyros are orthogonally mounted within the MARG unit to form a triad capable of measuring 3-DOF angular rate.

The design accelerometer is the micromachined Analog Devices ADXL202E [20]. It was chosen for a number of reasons. The maximum measurement range is +/−2g, which is acceptable for sensing gravitational acceleration. The ADXL202E is a two-axis acceleration sensor on a single chip. As a result, only two of them are required to form a triad for measuring 3-DOF acceleration. Its size is 4.5 × 5.0 × 1.8mm. The ADXL202E also offers a duty cycle output, which can be directly interfaced to a low-cost microcontroller without A/D converters. Additional discussion concerning the accelerometers in conjunction with the selection of microcontrollers appears below.

Honeywell offers a family of one and two-axis magnetic sensors. In the MARG design, a one-axis HMC1051Z [21] for the z-axis and a two-axis HMC1052 [22] for x-y axes are mounted on the same PCB to form a three-axis magnetometer. The dimensions of the one-axis HMC1051Z are 6.8 × 9.8 × 1.4mm, and those of the two-axis HMC1052 are 4.8 × 2.9 × 1.1mm. It is noted that the two-axis magnetic sensor is actually smaller than the one-axis sensor and it may seem better to use two two-axis magnetic sensors rather than one of each to construct a three-axis magnetometer. However, the HMC1051Z and HMC1052 are specially designed to be mounted on the same PCB to form an orthogonal triad. Using two HMC1052's requires them to be mounted on two orthogonal PCB's and would actually increase the overall form factor of the MARG unit.

The current design incorporates a microcontroller. The purpose of the microcontroller is to convert analog sensor outputs to digital data, digitally filter the angular rate sensor data, perform an automatic set/reset of magnetometers to avoid magnetic saturation problems, and implement all or part of the complementary filtering algorithm. In previous versions, the design did not include a microcontroller. Sensor unit output included nine separate analog signals. This required analog-to-digital conversion to be performed on a host computer and increased the thickness of the wiring bundle connected to each MARG unit. Magnetometer sets and resets had to be performed manually.

After an extensive tradeoff analysis, the MSP430F149 microcontroller manufactured by Texas Instruments was selected for incorporation into the MARG sensor unit [23]. It is an ultra-low-power, 16-bit RISC architecture microcontroller with 60KB of flash memory. Its dimensions are 12.2 × 12.2 × 1.6mm. Among other features, the MSP430F149 has eight 12-bit A/D converters, two timer modules, and two USART's (Universal Synchronous/Asynchronous Receiver Transmitter). Outputs of the three rate sensors and the three magnetic sensors are analog, and are connected to six of the eight A/D converter channels of the microcontroller. Each microcontroller timer module has one 16-bit counter and three capture/compare registers. The digital outputs of three accelerometers are interfaced to the three capture/compare registers of the first timer module. Interfacing the accelerometers with the timer module avoided the need to use a more complex microcontroller with 12 or 16 A/D channels.

Figures 1 and 2 depict the prototype PCB's of the MARG sensor. Each sensor consists of three PCB's. When assembled, the two square PCB's are stacked vertically and the rectangular one is mounted orthogonally. Figure 1 shows the top view of the three PCB's and Figure 2 shows the bottom view. The three large rectangular chips shown in Figure 2 are rate sensors, and the large square chip shown in Figure 1 is the microcontroller. As seen from these prototype PCB's, the ceramic rate sensors dominate the overall size of the current MARG design.

4. Linearity of Individual Sensor Components

The hardware and software design of the MARG sensor unit is based heavily on the assumption that responses of the individual sensor components are linear under the intended application conditions. If the sensor responses are linear, calibration of each sensor component simply requires determination of the null voltage value and the scale factor. Otherwise, a complicated nonlinear lookup table would be needed to map sensor responses to the corresponding motion inputs.

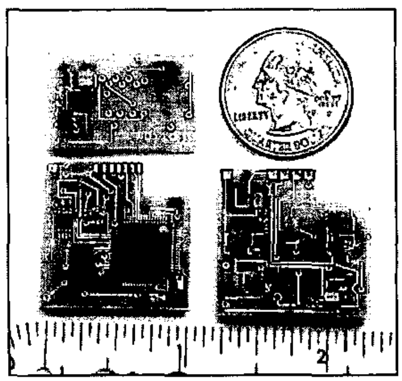

Figure 1: Top view of the MARG sensor prototype PCB's. Large square chip on the lower left PCB is the MSP430F149 microcontroller.

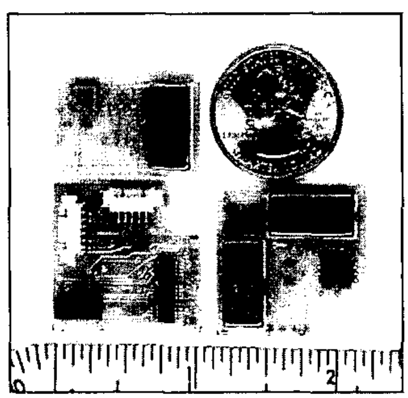

Figure 2: Bottom view of the MARG sensor prototype PCB's. Large rectangular chip on the top PCB and the two same chips on the lower right PCB are CG-L43 angular rate sensors.

Linearity testing results of the sensor components are presented in this section. All nine sensor components have been tested. Results from the z-axis angular rate sensor, the x-axis accelerometer, and the x-axis magnetic sensor are described in detail. Results for other sensor components are similar, and thus not presented.

Linearity testing was carried out using a Hass rotary tilt table [24]. The table has two degrees of freedom and is capable of positioning to an accuracy of 0.001 degrees at rates ranging from 0.001 to 80 degrees/second. In order to mitigate any possible magnetic field effects generated by the steel construction of the tilt table on the magnetic sensor, the sensor package was mounted on a non-ferrous extension above the table. The extension is made of a piece of PVC pipe and is approximately one meter in length as depicted in Figure 3.

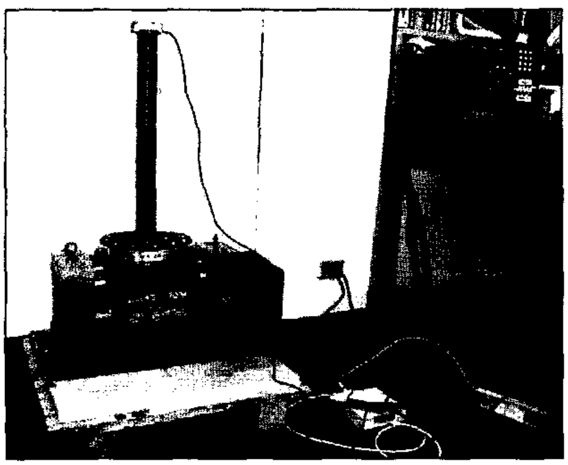

Figure 3: Testing setup of the Hass rotary tilt table with the MARG sensor mounted on a non-ferrous PVC extension tube.

The response of the angular rate sensors was tested by mounting the MARG sensor on the tilt table and rotating the unit about the sensing axis of each. A series of rotations at progressively higher rates was performed. The rotation sequence began with a negative 90 degree rotation at a rate of 10 degrees/second. After a still period of three seconds, the initial rotation was followed by positive 90 degree rotation at a rate of 10 degrees/second. After another still period, this pattern was repeated, with the rotational rate being increased by 10 degrees/second on each iteration until the maximum rotation rate of the tilt table (80 degrees/second) was reached. The resulting voltage response of the angular rate sensor versus time is plotted in Figure 4. Examination of the plot indicates that the null voltage while the sensor is stationary is about 2.855 volts. Increasing positive rates of rotation yield higher voltages and higher negative rates of rotation produce lower voltages. Figure 5 shows the plot of the tilt table rotation rates (i.e., −80, −70, …, +80) versus the corresponding rate sensor responses (average values). It clearly shows that the response of the angular rate sensor is linear through the range of -80 to +80 degrees/second.

The voltage response of the accelerometers was examined by mounting the sensor units on the tilt table and rotating them about a horizontal axis through 360 degrees. The purpose of these rotations was to allow the individual accelerometers to sense the gravity vector in all attitudes. Two types of tests were conducted. In the first tests, the rotation of the sensor was continuous at a rate of one degree per second. Figure 6 plots x-axis accelerometer voltage versus time producing a sine curve. In this experiment, the accelerometer started by sensing zero g's and moved through positive one g at 90 seconds and negative one g at 270 seconds. Since the x-axis accelerometer measures the gravity vector projected onto the x-axis, the voltage response should be an exact sine curve if the accelerometer is linear and free of noise. In Figure 6, the green curve is the accelerometer response, and the blue curve is the best-fitted sine wave. It is seen that the sine wave is tightly- fitted to response data, indicating that the accelerometer response is linear. To further illuminate the accelerometer linearity, Figure 7 shows the plot of the computed rotation angle versus time. The rotation angle is computed by using the inverse of the fitted sine function and applying it to the accelerometer data. The horizontal axis of the plot, i.e., time, is equivalent to the tilt table rotation angle because it is rotated at a rate of one degree per second. Examination of Figure 7 indicates that the accelerometer response is clearly linear.

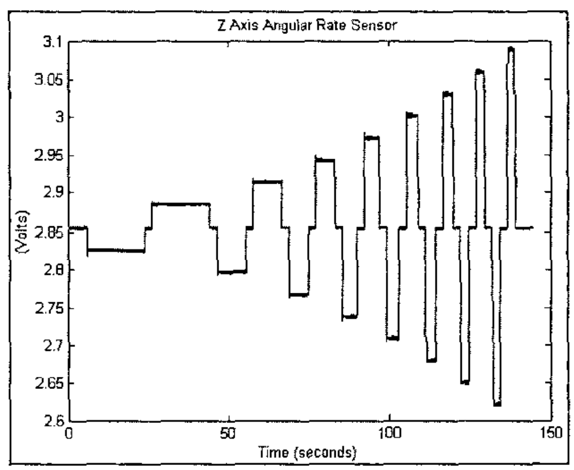

Figure 4: Voltage response of the Z axis angular rate sensor subjected to increasing magnitudes of rate change.

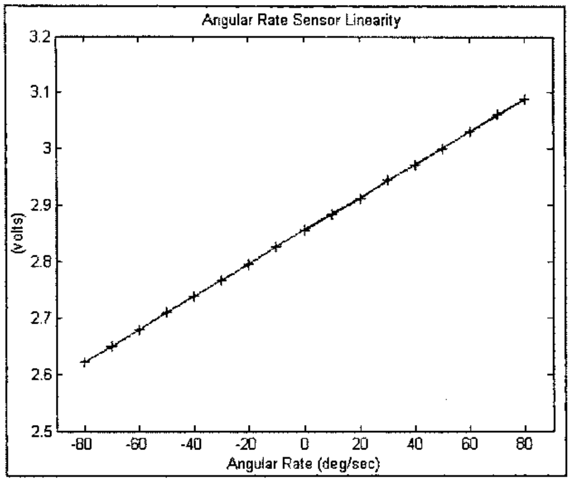

Figure 5: Plot of tilt table rotational rate vs. response of Z axis angular rate sensor.

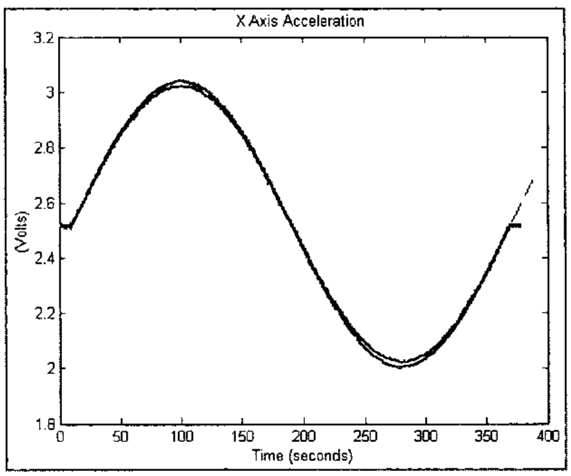

Figure 6: The response of the x-axis accelerometer (thick green curve) and the best-fitted sine wave (dashed thin blue curve), resulting from the first experiment with continuous rotation at a rate of one degree per second.

In another accelerometer test, the rotations of the MARG unit were accomplished in incremental steps of ten degrees. In between each of these steps the sensors remained static for a period of ten seconds. Figure 8 is a plot of the sensor output voltage versus time from one of these tests. Examination of Figure 8 reveals that with each ten degree change in the attitude of the sensor, the output voltage changes by a fixed amount of approximately 0.1875. Results from this experiment indicate that the response of the accelerometers is linear.

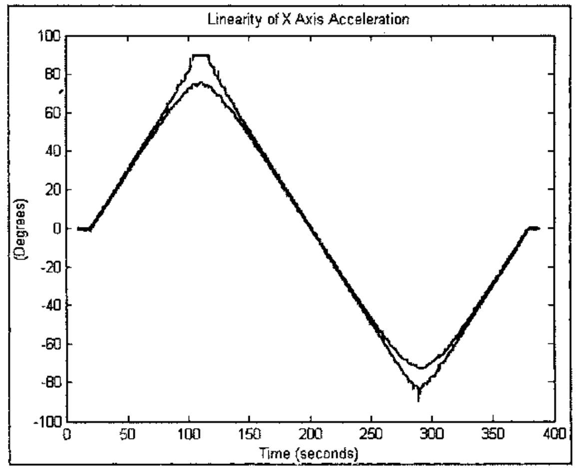

Figure 7: The computed rotation angle using the x-axis accelerometer response, depicting linearity of the accelerometer.

During the accelerometer tests described above, the plane of rotation was aligned with the local magnetic field vector. Magnetic sensor data were also recorded. The responses from magnetic sensors are similar to those of accelerometers. At any given location, the earth magnetic field is a fixed vector. The response of the x-axis magnetic sensor is the projection of the fixed earth magnetic vector onto the sensor x-axis. Figure 9 shows the response of the x-axis magnetic sensor as a result of the tilt table rotation about a horizontal axis at a rate of one degree per second. In a depiction similar to Figure 6, the thick green curve is from the actual magnetic sensor data, and the thin blue curve is the best-fitted sine wave. If the magnetic sensor is linear, the response should again be a sine wave. It is seen from Figure 9 that the magnetic sensor response is very close to a sine wave, indicating that it is linear.

Based on the experiments and results presented above, it is concluded that the sensor components used in the design of the MARG unit are linear. In the next section, a simple calibration method is presented, which determines the null voltage value and the scale factor without using precision calibration equipment such as the Hass tilt table described in this section.

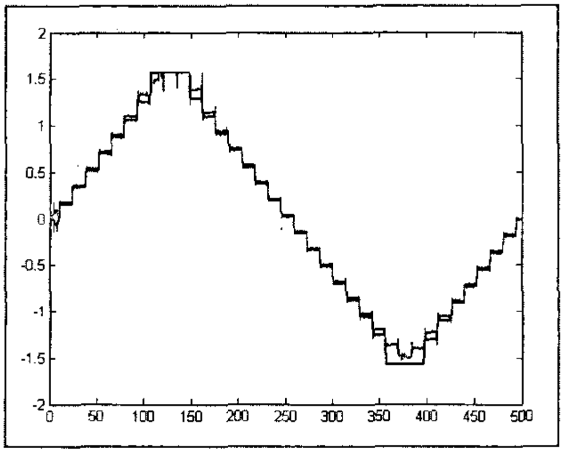

Figure 8: The response of the x-axis accelerometer, resulting from the second experiment with incremental rotation steps of ten degrees.

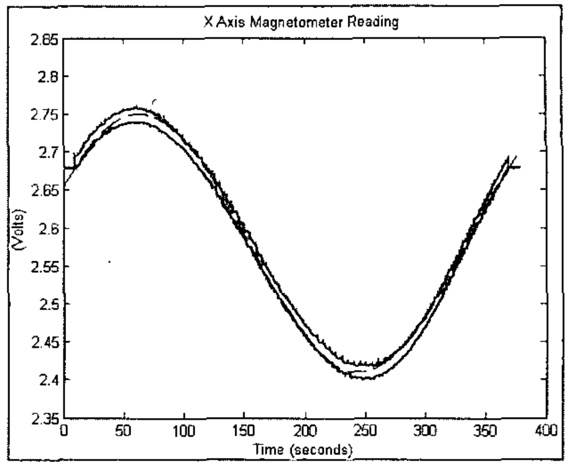

Figure 9: The response of the x-axis magnetic sensor, resulting from the first experiment with continuous rotation at a rate of one degree per second.

5. Sensor Calibration Method

MARG unit calibration requires determination of the null point and scale factor of each individual sensor component. Unless the characteristics of the sensors themselves change, calibration of the individual components need only be accomplished once. The MARG sensor calibration method is designed to be accomplished by hand without the aid of specialized equipment. It consists of placing the sensor unit in a series of predetermined orientations and subjecting it to several rotations about single sensor axes.

An individual linear accelerometer can be calibrated by placing it in a vertical position to sense gravity in one direction and then turning it over to sense gravity in the other. Halfway between the maximum and minimum readings taken is the null point which can be derived from

$$accel\,null = \frac{accel\,max + accel\,min}{2} \qquad (1)$$

and verified by placing the accelerometer in a horizontal position that is perpendicular to the gravity vector. Multiplication of a correct scale factor times the accelerometer output values should result in a product of 1 g in one direction and -1 g in the other. This value can be derive using

$$accel\,scale = \frac{(accel\,units) \times 2}{accel\,max - accel\,min} \qquad (2)$$

which is again based on the maximum and minimum readings of the accelerometer when aligned with the gravity vector. This scale factor can be interpreted as the slope of the central part of the sinusoid in Figure 6.

An obvious method of magnetometer calibration is very similar to that used for accelerometers. Instead of orienting each sensor relative to the gravity vector, each magnetometer would have to be placed in a position in which it can sense the maximum strength of the local magnetic field along both its negative and positive axes. The exact orientation of the local magnetic field vector with respect to the vertical is not as apparent as that of the gravity vector. Therefore, sensing the maximum strength of the field requires that the magnetometer be slowly rotated in a plane containing the magnetic vector while recording the maximum and minimum voltage readings obtained.

If it is assumed that bias drift is not present, the null point of an angular rate sensor can be determined by recording and averaging over some time period the output of a static sensor. In the case that the null point is not stable, a low pass filter is required and this statically determined null point can serve as an initial estimate. Scale factors can be estimated by integrating the output of the angular rate sensor as it is subjected to a known rotation. The scale factor based on this known rotation is given by

$$scale\,factor = \frac{known\,rotation}{estimated\,rotation} \qquad (3)$$

where the estimated rotation term is the result of integrating the output of the sensor with a scale factor of unity through out the period during which the known rotation is taking place.

From the above and the linear characteristics of the individual components, it is apparent that a MARG unit can be completely calibrated using a level surface and a simple compass to indicate the direction of the local magnetic field. In the method implemented, each sensor was calibrated by placing it in six positions which allowed each accelerometer to sense gravitational acceleration in both the positive and negative directions, subjecting each rate sensor to two known rotations and rotating the MARG sensor in a manner such that maximum and minimum local magnetic field readings could be obtained for each magnetometer.

To verify the accuracy of the calibration procedure when performed by hand, it was also completed using the Hass rotary tilt table to perform all rotations and do all positioning. In these experiments a MARG unit was calibrated ten times by hand and ten times by machine. With the exception of the rate sensor scale factors, the averages and standard deviations for the all parameters were statistically equivalent for hand and machine calibration. Though the standard deviation for rate sensor scale factors was somewhat larger for hand calibration, the average values were also statistically equivalent. It is hypothesized that this difference was most likely due to the imprecise measurement of the exact angle of rotation and additional vibration during the hand calibrations trails. However, given the quickening role [5] played by the angular rate sensors in the body tracking application, the differences between hand and machine calibration were not considered significant.

6. Current and Future Work

Efforts over the next year will center on integrating 15 MARG sensors into a single system and further reducing MARG unit form factor. The goal of these efforts will be to produce a full body tracking system. The system will not tether a tracked subject to a fixed workstation, thus allowing posture tracking over a wide area. It will also allow experimentation with precision heading devices and sensor data fusion to reduce any susceptibility to variations in the local magnetic field.

The dimensions of the Tokin CG-L43 angular rate sensor limit the size to which the MARG sensor unit can be reduced. Currently the authors anticipate the release of a micromachined rate sensor in the spring of 2003. This component is expected to have performance that is superior to the ceramic gyro currently being used in the MARG design. Use of this component will allow the form factor of the MARG unit to be further reduced for two reasons. Dimensions are expected to be on the order of 7 x 7 x 3mm. In addition to the size reduction that will be achieved due to the smaller dimensions, the physical principles on which it is based will allow components to be more tightly packed since acoustic coupling between the rate sensors will no longer be a concern. It is expected that incorporation of this sensor will produce a unit that is roughly the size of a wristwatch.

Full body motion tracking will require the integration of approximately 15 MARG sensors into a single system. Efforts are currently underway to build a data control unit (DCU) that will collect data from all sensors. Currently plans call for the DCU to output data in USB format to a wearable PC. The wearable PC will then transmit tracking data using an 802.11b wireless PCMCIA card to a fixed workstation. The workstation will act as a server of posture data in conjunction with a networked virtual environment. Only the distance over which the wireless LAN can operate will limit the range of this system.

7. Summary

The design and implementation of the Magnetic, Angular Rate, and Gravity (MARG) sensor have been described. The MARG sensor is a small, 3-DOF orientation sensor constructed from three angular rate sensors, three accelerometers, and three magnetometers. Testing results regarding the linearity of sensor components are presented. It is shown that all sensor components are linear within the intended operating conditions. Based on the linearity property, a simple calibration method is proposed. Using this method, the null voltage value and the scale factor of each individual sensor component can be obtained without the need for precision calibration equipment.

The MARG unit itself is a general purpose 3-DOF orientation sensor that has many potential applications in robotics and other fields. This work is currently focused on human body motion tracking. It is planned to attach fifteen MARG sensors, one on each major human body segment, to track the motion of the entire human body in real time. The authors believe that MARG sensors and the associated data processing algorithms will have important applications to human body motion tracking, teleoperation, virtual reality, and entertainment.

Acknowledgment

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