THE INERTIAL NAVIGATION UNIT: TEACHING NAVIGATION PRINCIPLES USING A CUSTOM DESIGNED SENSOR PACKAGE

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Abstract

This paper describes the application and design of a small, inexpensive inertial navigation unit (INU) created to introduce systems engineering students at the United States Naval Academy (USNA) to the principles of navigation systems and to act as a navigation sensor for robotic and autonomous vehicle projects. The INU has been used in place of a multitude of standard navigation sensors such as an inertial measurement unit (IMU), magnetic compass module, and Global Positioning System (GPS) receiver. Its integrated design simplifies mechanical mounting, reduces navigation system weight and size, simplifies data interfacing with a control computer, and provides great flexibility for reconfiguring to meet a variety of engineering education objectives. The INU is capable of firmware upgrades and algorithm enhancements in the field via in-circuit programming, enhancing its longevity as a useful educational tool. In addition, a variety of controllers or a personal computer (PC) can communicate with the INU board through a standard RS-232C serial interface. This compact unit provides good system performance at a reasonable cost compared to most commercially available units. These features enable hands-on education techniques in the navigation aspects of robotics, examples of which are presented.

Introduction

A significant amount of work in robotics is done in the USNA Systems Engineering Department, with autonomous vehicles in particular. Such ABET accredited engineering programs require a “capstone” design project for graduation, and each year there are numerous student projects to build autonomous vehicles of various types. Several student independent research projects are also completed each year. Supporting these projects is a senior-level elective course in autonomous vehicles in which students are exposed to the principles of vehicle navigation and provided hands-on experience with navigation system components. Navigation systems commonly include an IMU, a combination of accelerometers and gyros to sense vehicle translational and rotational motions without external reference. Other navigation components commonly found on autonomous vehicles include a magnetic compass as a heading reference and a GPS receiver for position and velocity measurement. The need for small and inexpensive, yet capable, navigation systems in this department are therefore necessary.

To meet this need, a navigation sensor package was developed and built “in house”. A printed circuit board was manufactured locally and populated with readily available components to produce a compact, low-cost inertial sensor module that meets these requirements in all but a few of the most demanding applications. The INU is based on Microchip’s dsPIC30F4013 digital signal processor[1] and commercially available sensors. The INU is less than 2” x 3” x 1.3”, weighs less than 1.6oz, costs under $300 for parts, and has an update rate of 80Hz. The system provides 6-axes of inertial sensor data, GPS, a real time clock (RTC) for data stamping, magnetic compass, and temperature sensing, making it an ideal circuit board for embedded applications. The system integrates analog and digital sensors, serial communication interfaces and protocols, and a user command interface.

In this work we outline the development of a digital signal processor-based navigation system and describe its capabilities. We also describe its application in student work, particularly as the basis of laboratory experiments in a course on autonomous vehicles.

System Description

Our research combines low cost readily available components to provide a sensor system capable of improving embedded computing applications and enhancing laboratory experimentation. The dsPIC Inertial Navigation Unit (Figure 1) acquires and processes various sensor data to be transmitted to an external control unit such as a microprocessor board or PC, for purposes of state estimation and navigation. The navigation system can be configured by the external control unit to meet the user application and to provide a high-level of sensor information.

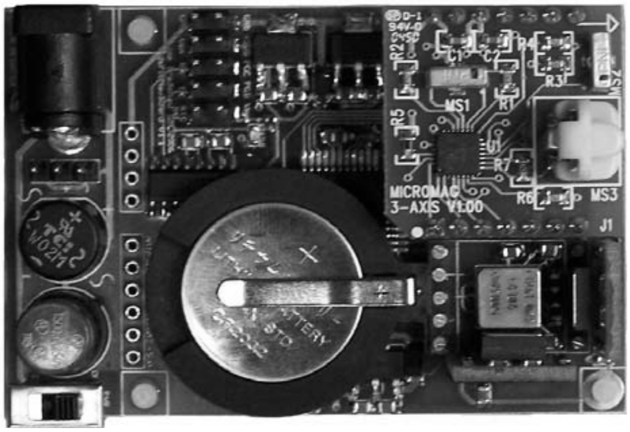


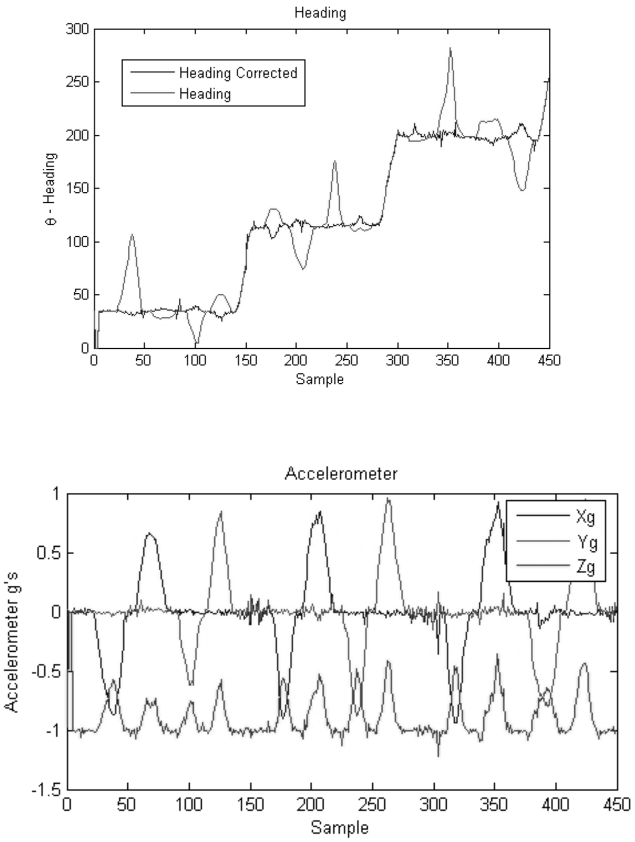
Figure 1 – A top view of the complete Inertial Navigation Unit. The three Analog Device's ADXRS300 gyros, MicroMag3 magnetometer, 3 volt backup battery, power supply, and communications port are visible.

Hardware Description

The dsPIC Inertial Navigation Unit (INU) utilizes a Microchip dsPIC30F4013 digital signal processor to gather sensory data from analog and digital sensors for purposes of state estimation and to improve control system capability in the area of navigation. The circuit board is equipped with 3-axes of acceleration measurement from an MMA7260Q micro-machined accelerometer from Freescale^{TM} Semiconductor. Roll, pitch, and yaw rates are measured with 3 Analog Devices ADXRS300 rate gyroscopes with internal signal conditioning. A MicroMag3 3-axis magnetic field sensor module is used as a digital compass for heading indication. Also implemented is a Trimble Lassen® iQ 12-channel GPS receiver with an on-board backup battery. A National Semiconductors LM34 or LM35 precision temperature sensor allows for precise temperature measurement and calibration of analog sensors under varying environmental conditions. Data is gathered and transmitted serially by the dsPIC30F4013 at 115200 8N1 baud rate by means of the level-shifted serial port at an update rate of 80Hz in the standard North-East-Down coordinate frame convention. The serial port can also be placed in a command mode. A Dallas Semiconductor DS1390 SPI interface RTC is used to time stamp data and aid in special event recording. Four independent voltage regulators are used to separate analog from digital supplies, aiding in digital noise isolation from inertial analog sensor circuits. The populated circuit board weighs 1.370oz without the GPS antenna (version 1.1 containing the power connector, fuse, bridge rectifier and switch weighs 1.585oz).

The MMA7260Q accelerometer on the INU employs an on-board single pole switch capacitor filter, temperature compensation, and g-select pins for output sensitivity selection of 1.5g/2g/4g/6g. The accelerometer has a low current consumption of 500µA and runs from a 3.3V regulator. The accelerometer is used for detecting the angle of the INU with respect to gravity by calculating the arc-sine of its X and Y g-measurements. A single pole digital low-pass filter is also used on output calculations to reduce accelerometer bandwidth response in tilt measurement. The low-pass recursive filter constants are calculated from the cutoff frequency using calculations derived from "The Scientist and Engineer's Guide to Digital Signal Processing[2]." The accelerometer should be placed as close to the center of rotation of the system being measured as possible to keep rotational influences on the accelerometer at a minimum.

A Precision Navigation Instruments MicroMag3 magnetic field sensing module[3] shown in Figure 1 is used to derive magnetic north from the Earths magnetic field. The module uses a serial peripheral interface (SPI) full duplex synchronous serial port communications protocol. The dsPIC30F4013s SPI port is configured for an 890KHz clock rate in 8-bit mode. Each axis of the sensors output is a measurement in micro-Tesla (µT) and depends on the gain set by 3 period select bits in the control word. These bits determine the number of counts per µT effectively scaling the resolution of the sensor axis to be measured. After the command word that determines the resolution and axis is transmitted to the MicroMag3, a delay ranging from 340µs at the lowest resolution (L/R 32 division ratio) to 28.65ms at the highest resolution (L/R 4096 division ratio) is employed followed by a Data Ready Line (DRDY) going to a high state. An external interrupt is used on the DRDY line so the dsPIC still processes data during compass measurement acquisition and only spends approximately 23µs reading the result and giving a new command word for the next axis to read. The application of this DRDY line on an external interrupt greatly increases the overall throughput of the INU. Two compass values can be transmitted in the data string. The first is the calculated value using low-pass filtered accelerometer measurements to determine instantaneous roll and pitch angles. These angular measurements are applied to magnetic compass measurements and use a rotational transformation to translate compass values to the horizontal plane, correcting for induced angular error[4]. The second compass measurement is the arc-tangent of raw Y over X magnetic measurements and will have an error relative to the tilt angle with respect to the horizontal plane. This compass value, however, is not influenced by accelerometer measurements (Graph 1).



Graph 1 – Graph of the accelerometer corrected heading vs. raw magnetic heading with applied angular rotation (samples taken at approximately 16 milliseconds).

Analog devices ADXRS300 rate gyros[5] were chosen for rotational rate information due to their small size, relatively low cost (less then $40 ea.), availability, and reliability. The gyros output an analog voltage directly proportional to angular rate in deg/sec (5mV/deg/sec) applied normal to the top surface of the BGA (Ball Grid Array) package. Roll and pitch gyro boards are mounted perpendicular to each other and vertical to the top surface of the INU board. The yaw gyroscope is mounted horizontal to the INU board directly over the accelerometer.

A Trimble Lassen® iQ GPS module[6] was chosen for its size and availability. The GPS module initializes in Trimbles proprietary TSIP mode, which is a binary serial protocol. The module is placed in NMEA-0183 mode through a series of commands and will retain an almanac for satellites with a backup battery once acquired. The module is capable of tracking up to 12 satellites and uses an external active antenna. GPS data is updated at a rate of 1Hz when available.

A DS1390 Trickle-Charge Timekeeping Chip[7] from Dallas/Maxim is used as a RTC for the INU. The date and time can be set to time stamp transmitted data for accurate recording to the hundredths of a second. The DS1390 uses a variation of SPI communications bus and needs to be configured appropriately before data transfers.

The dsPIC uses a 12-bit Successive Approximation converter running in channel scan interrupt mode updating all 13 analog channels every 142.8uS (7.003KHz). The dsPIC30F4013 Timer3 period register is set up to match after 12.5ms. When the Timer3 interrupt flag is set and 12.5ms has elapsed, the most current data is used in inertial/spatial calculations and the resulting information is transmitted serially in NMEA ASCII format: “$DSPNB,” header, the corrected compass value, uncorrected compass value, X-axis, Y-axis, and Z-axis acceleration in g’s, roll rate, pitch rate, and yaw rate in deg/sec, latitude data, longitude data, the current time, temperature in degrees, the current sample number, and an asterisk (*) followed by the hexadecimal checksum of all the characters in the string before the asterisk, a carriage return (0x0d, ‘\r’) and a linefeed character (0x0a, ‘\n’). All the components in the data string are comma delimited. Each parameter can be individually turned on or off through a command set interpreted by the dsPIC processor. Commands are sent as ASCII strings to the dsPIC30F4013 Navigation Unit and are executed upon the reception of a carriage return. The board can also be placed in a command mode upon which the processor requires a single carriage return before transmitting the data.

Software Description

The dsPIC® 30F4013 microcontroller from Microchip is programmed using Microchips MPLAB® Integrated Development Environment with the C30 full-featured ANSI compliant C compiler. The microcontroller can be reprogrammed in the circuit via ISP (In-circuit Serial Programming) connector. This allows for future firmware updates and software expandability.

Upon power-up or hardware reset the microcontroller program initializes variables and configures the hardware peripherals such as the general purpose I/O pins, the SPI communications port, two serial ports, and the analog-to-digital converter. Then the program enters an endless software loop which checks for serial commands, processes analog (rate gyros, accelerometers, temperature) and digital (MicroMag3 compass, GPS, RTC) sensor information. Analog to digital converter values are converted to voltages, then corresponding output parameters. Gyros output °/sec rate, accelerometers output volts/gravitational g measurement. Individual output parameters can be turned on and off through a serial command interface. These parameters are then individually concatenated to a string of ASCII characters and transmitted serially to the external control unit. The serial command interface also provides provisions for setting the RTC, and recalibrating the offsets for the inertial sensors.

Several microcontroller peripherals are modularly broken up into interrupts, such as the analog-to-digital converter scan interrupt, MicroMag3 compass data ready line external interrupt, the serial communications port character reception interrupt, and the GPS module character reception interrupt. Using interrupts to control certain functions increased the overall throughput and simplified software task management of the system.

Performance in the Lab

Along with successful application in autonomous vehicles, the INU has been used in the ES456 autonomous vehicles course as the basis of an IMU laboratory. In the lab it is used to familiarize students with accelerometer and gyro sensors and to demonstrate the mathematical principles in navigation algorithms. In this laboratory is it configured as an IMU, without the need for the compass and GPS hardware. The INU is used in conjunction with a 3-axis rotational gimbal locally constructed of PVC plastic (Figure 2).

The lab uses the Windows HyperTerminal program to communicate with the INU through the PCs RS-232C serial COM port. Students type commands and receive data through a basic textual interface which is augmented at times with a text capture file. Once HyperTerminal is correctly set up for the INU serial protocol (115200 baud, 8N1) and power is applied to the board, striking the "Enter" key returns a single line of data in NMEA-0183 text format consisting of comma-separated measurements from all three sets of accelerometers and gyros, followed by a checksum. Initially, students make some general observations of accelerometer measurements by changing the INU attitude and eventually identify the orientation of its 3 axes. As the lab uses only the accelerometers and gyros for data analysis, other data fields for other navigation sensors are disabled. This is done by initially issuing the "ALLOFF\r" command, then enabling the individual X, Y, and Z accelerometers by issuing the "XGON\r", "YGON\r", and "ZGON\r" commands respectively.

Once accelerometer axes are identified and sketched, students can align the INU with the PVC rotational gimbals roll, pitch, and yaw axes in the North-East-Down convention with roll around the X-axis. Once mounted, the gimbals are used to input specific Euler angles and students can apply their knowledge of coordinate transformations to predict the

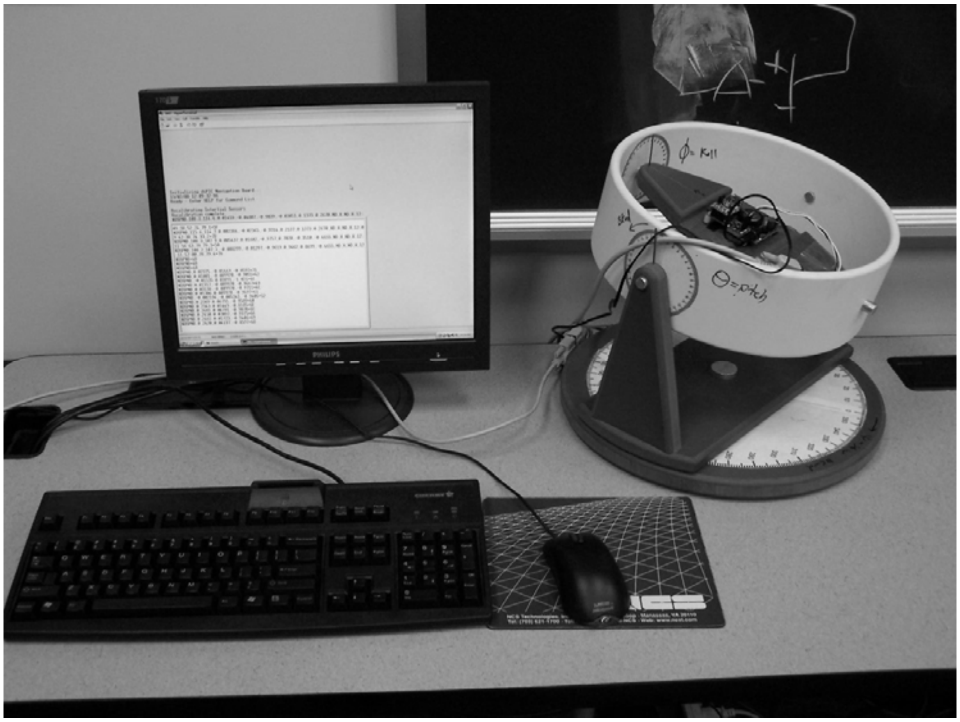


Figure 2 – The INU positioned on the PVC rotational gimbals in the lab.

rotation of the gravity vector from the global frame to the IMU body-fixed frame. The inverse can also be performed, allowing students to compute static vehicle attitude by sensing of gravity components with the 3 INU accelerometers and calculating the Euler angles.

Although gravity is a convenient and quantified input to the INU accelerometers, there is currently no such convenient input to the INU rate gyros. Instead, integration of gyro rate is used by rotating through a known angle to demonstrate gyro principles. As the INU is rotated through a known angle, its rate measurements are sent both to the computer screen as well as to a text capture file. The captured rate data is then exported to a spreadsheet where it is numerically integrated. Comparing the integrated rate data to the known angle of rotation allows evaluation of the global rotational velocity vector as rotated into the body-fixed frame of the INU. For example, when the INU is level and rotated 180° about the gimbals vertical axis, the Z gyro integrated angular rate is approximately 180° and the integrated rates of the other gyros are approximately zero. However, inserting a pitch or roll angle into the gimbals reduces the Z gyros rate while increasing the X or Y gyros rate respectively.

In another lab, the INU is used to teach students rudimentary Kalman filtering of sensor data. In this lab both gyro data, which is subject to drift error, and compass data, which is subject to magnetic anomalies, are filtered to provide an estimate of heading.

Conclusions and Future Work

In future work numerous enhancements can be made on this navigation unit. A few improvements presently underway include the application of a discrete Kalman filter[8] on the output data to provide optimal state estimation[9]. A motorized gyroscopic test platform is currently being developed to provide continuous yaw axis rotation and +/- 90 degrees of pitch and roll rotation for rate gyro testing. Such an apparatus would aid in quantitative data collection from the INU for statistical parameter acquisition, enabling enhanced algorithms and on-board program calculations. Presently a MATLAB program capable of displaying the INU motion real time and graphing sensor data has been written for demonstration and preliminary data analysis. Work is also being done to incorporate a software complementary filter on the accelerometer and gyro measurements.

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