GPS and Inertial Navigation

Functional Description and System Block Diagram

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Introduction

The ability to navigate accurately has been required for centuries. Recent advances in technology have allowed for new navigation systems to be developed for determining position and attitude of a body. The advent of GPS satellites has provided a low cost method for consumer navigation. Yet, there are occurrences where GPS signals are unavailable and a different method must be implemented for navigation. The standard solution before GPS based navigation was an Inertial Navigation System (INS). INS systems have been used for navigation on many major projects including systems such as space vehicles and aircraft. An INS system measures a body's accelerations and rotational velocities to determine the position and attitude of the body. Recent advances in MEMS technology has allowed for cheap, silicon-based accelerometers making an INS system an attractive choice for environments where space is a consideration, or other systems such as GPS signals are not available.

The combination of GPS and INS allows for a highly accurate system that can mitigate the drawbacks of both systems. INS provides a description of the body's accelerations and angular rates, and can detect near instantaneous changes in orientation. Current MEMS sensors, however, tend to be very noisy and can only provide short term stability for an INS solution. Heavy statistical processing is required to make good use of the MEMS accelerometer outputs. A GPS system on the other hand, also provides a description of a body's position, but has a much slower refresh rate than that of any typical INS. A coupled system can be constructed by taking advantages of each system's strength. Such system can survive frequent GPS signal outages and improve position and attitude estimates

Objective

The objective of the project is to fuse GPS and INS. The final system will be able to take data from a GPS receiver and an Inertial Measurement Unit (IMU) containing accelerometers, gyroscopes, and magnetometers, and continuously compute the body's position and attitude. The system will be able to provide a high accuracy navigation system that can operate over a long period of time.
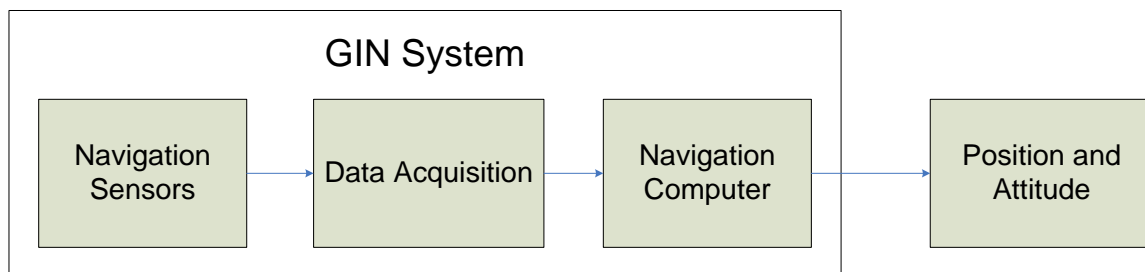
Functional Description

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Figure 1: Overall System Block Diagram

A navigation system consists of three major components; the sensors, data acquisition system, and the navigation computational component. The navigation solution is provided through the disturbance of the sensors, with time-stamped measurements taken by the data acquisition system, and finally the computation of the position and attitude by the navigation computer. How the computer utilizes the different sensors can be accomplished in either a loosely-coupled or tightly-coupled manner.

The fusion of the two sets of navigation sensors will be first accomplished in a loosely-coupled manner, reserving the tightly-coupled manner for future system expansion. The manner in which the sensors are coupled details how the INS utilizes the GPS data. In a loosely-coupled system, the GPS based position solution is computed independently and used as a single state in the Kalman filter, while in a tightly-coupled system, the system filter utilizes individual GPS signals as state variables. The loosely-coupled system will be implemented first, and the block diagram of this system is shown in Figure 1. This project focuses on the implementation of the loosely coupled system. Upon completion and verification of the loosely coupled system, additional system expansions will be looked at. Time remaining will be the deciding factor in choosing an expansion to pursue, which include non-linear Kalman filtering and a tightly coupled design.   The block diagram of a closely-coupled system is shown in Figure 2. A long term goal, outside the scope of this project, is to realize the GIN system on a standalone microcontroller / FPGA board.

To utilize the INS information of the position and attitude, initial position and attitude data are needed by the system. Data can be gathered from the standalone GPS unit, as well as magnetometers for attitude determination. For the first system implemented utilizing post processing, the initial position and attitude can be entered manually. As the system furthers development, initial computations will be performed upon startup to allow for a standalone system. A detailed system diagram can be seen in figure 2.

Sub System 1 – Navigation Sensors

Four sets of sensors are utilized in the system. The sensors are three axis accelerometers, three axis gyroscopes, three axis magnetometers, and a GPS receiver. To provide the accelerometer, gyroscope, and magnetometer readings along the three axes, a VectorNav VN-100 will be utilized. The VN-100 consists of an attitude and heading reference system (AHRS) built on surface mounted chip. As an AHRS, the VN-100 can provide a complete positioning and attitude solution, and contains MEMS based accelerometers, gyroscopes, and magnetometers. While an accurate solution can be obtained from the chip, the VN-100 is used only for the three sensor readings. A VectorNav development board for the VN-100 is provided to allow access to the individual pins and functionality of the chip. The GPS receiver currently chosen for the project is the uBlox EVK-5 evaluation kit. The package computes and outputs the GPS position solution. Further research is being conducted as to whether or not the EVK-5 can output individual satellite signals for the closely coupled solution. A new GPS package may be necessary for the tightly-coupled system.
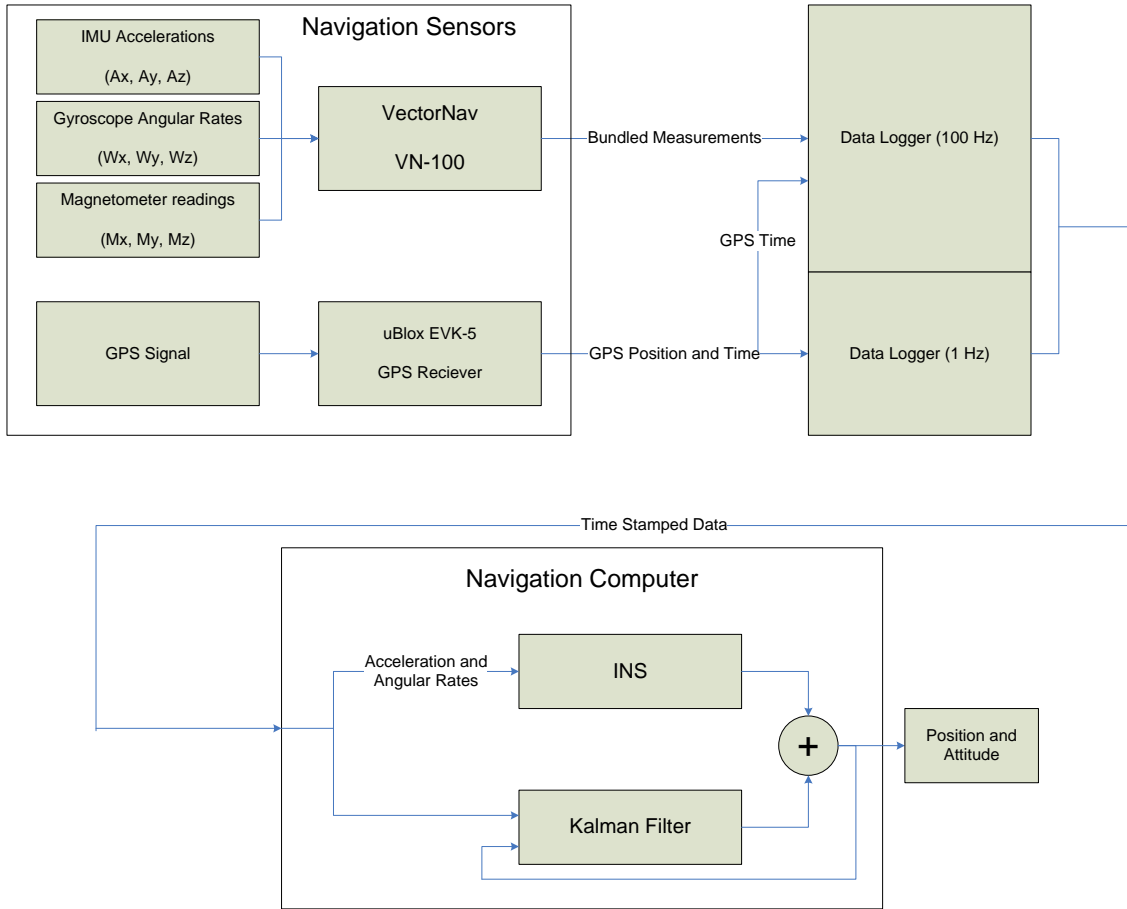
Navigation Sensors

IMU Accelerations (Ax, Ay, Az)

Gyroscope Angular Rates (Wx, Wy, Wz)

Magnetometer readings (Mx, My, Mz)

VectorNav VN-100

Bundled Measurements

GPS Signal

uBlox EVK-5 GPS Reciever

GPS Position and Time

Data Logger (100 Hz)

GPS Time

Data Logger (1 Hz)

Time Stamped Data

Navigation Computer

Acceleration and Angular Rates

INS

Kalman Filter

+

Position and Attitude

Figure 2: Detailed System Diagram

Navigation Sensors

IMU Accelerations (Ax, Ay, Az)

Gyroscope Angular Rates (Wx, Wy, Wz)

Magnetometer readings (Mx, My, Mz)

VectorNav VN-100

Bundled Measurements

GPS Signal

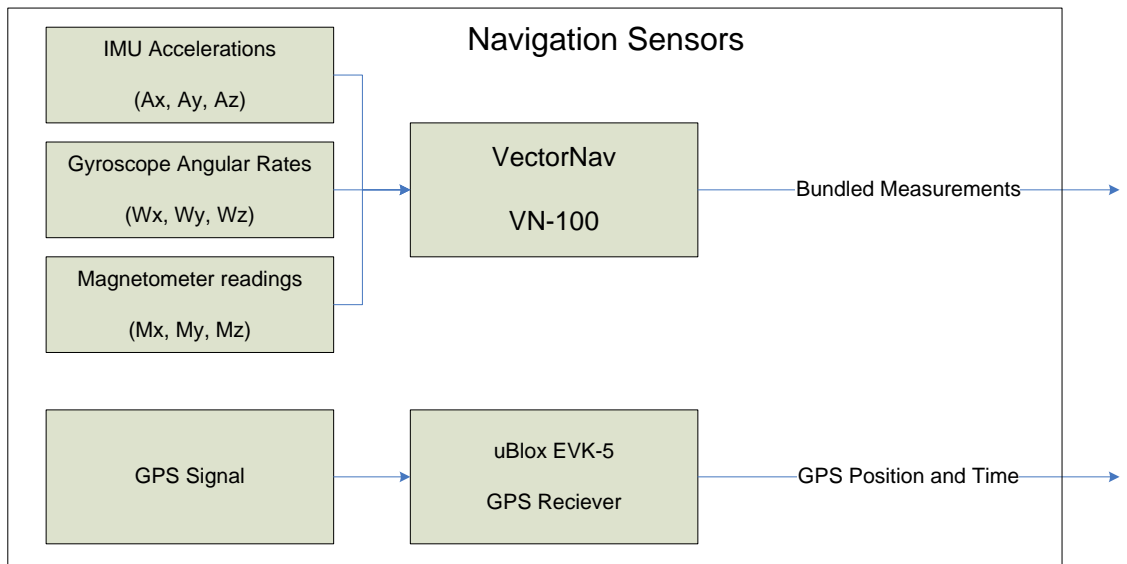uBlox EVK-5 GPS Reciever

GPS Position and Time

Figure 3: Navigation Sensors Subsystem

Sub System 2 – Data Acquisition

The data from both the IMU and GPS receiver will be fed to a data logger. Both systems operate at different frequencies; the IMU typically at 100 Hz, and the GPS at 1 Hz. The data logger will collect navigation data and assign time stamps to both IMU and GPS data. This will provide a method in which to correctly align the data under a common time scale needed for filtering to be performed in a recursive manner.

Different options exist for the Data Logger solution. The basic requirements of the system include the ability to simultaneously communicate with the IMU and the GPS components, as well as establish the arrival times for the information. For communication purposes, the VN-100 supports both SPI and UART protocols, while the EVK-5 only operates with UART. Proposed systems such as the SparkFun Logmatic data logger and other commercially available data loggers provide methods for recording data over the UART and SPI protocols. So far, a commercial system has not been found that can do simultaneous recording while remaining cost effective. Similar GPS/INS systems have been implemented utilizing an FPGA as a data logger. The FPGA solution offers a few key benefits. First, full control over how the system functions is achieved by having to design it. Second, the PPS and GPS timing signals can be utilized as a synchronization clock for the system, and provide a tighter timing specification and more accurate time stamping. Finally, the FPGA solution provides the possibility of expansion if a standalone system is desired.

Sub System 3 – Navigation Computer

The navigation computer executes all computations necessary in determining the system outputs. Three sub components make up the navigation computer, the INS, the Kalman filter, and the GPS module. In the first iteration of the GIN system, all data will be post processed using MATLAB. Data analysis and system modeling will be continuously performed to increase the accuracy of the system description. This will provide a better model for the Kalman filter to operate on.

Navigation Sub System 1 – INS

An INS is the primary provider of the position and attitude solution. The INS will take the measurements from the IMU and sequentially compute the body's position and attitude. The INS will be configured as a strap-down system. A strap-down system is a system in which the accelerometers are fixed directly to the body in a known orientation. A rotation matrix is then used to orient the accelerometers to the earth-fixed navigation plane used for navigation. The INS operates by continuously integrating acceleration and angular rates to provide the distance traveled and angles turned. Additional math and signal processing must be done to account for the accelerations due to gravity and the angular rate errors due to the rotation of the earth. The initial implementation of the INS will occur using MATLAB.

Navigation Sub System 2 – Kalman Filter

The Kalman filter is the primary tool utilized to obtain state estimates of the system. Kalman filtering is a method to minimize the inherent noise in the sensors and system using knowledge of the system dynamics combined with observation of the system. The design of the Kalman filter will allow for estimates of the position and attitude error to be available by utilizing all the data from the sensors. These state estimates will be combined with the data from the INS to provide a greater accuracy in position and attitude. A basic Kalman filter operates on the assumption that the system is linear. Variations on the filter exist for nonlinear systems (extended Kalman filter and linearized Kalaman filter) and highly nonlinear systems (unscented Kalman filter). With the progression of the system design, the linearity of the navigation system will be explored and a decision between the basic, extended, and unscented Kalman filter will be made.

The amount of data sources will determine how many states the Kalman filter will have. In the initial implementation of the Kalman filter, the states of the system will be estimated using the measurements of the IMU and GPS. As the project progresses, the system will be modeled further and the number of states increased.

Navigation Sub System 3 – GPS

As discussed earlier, the GPS subsystem will be used in both the loosely and tightly-coupled configurations. In the loose configuration, the GPS will operate as a standalone receiver and position computer. The position data will be inputted directly to the Kalman filter in order to estimate the error states. In the tight configuration, the GPS signals will be inputted directly to the Kalman filter for error state estimation. All computations and signal processing for the GPS will be internal to the GPS module and will not be altered.
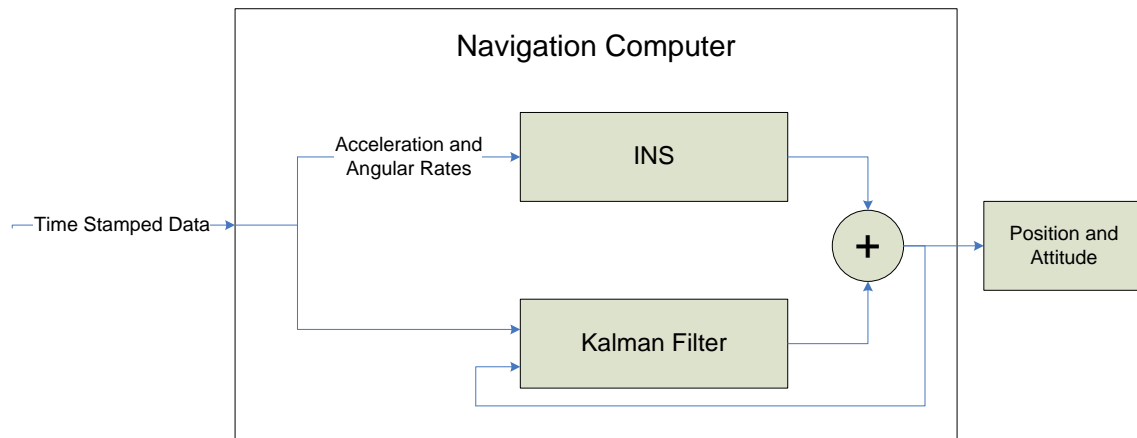

Figure 4: Navigation Computer Subsystem

Conclusion

The work on the GIN system is currently divided among three fields of the FPGA data logger, strap-down INS, and Kalman filtering. The data logger is currently the most critical component as it will provide data sets necessary for the design and implementation of the INS and Kalman filter. A basic INS will be the next component designed and implemented. This system will utilize the necessary transformations and mathematics to produce position and attitude estimates from the raw data sets. Finally, the Kalman filter will be implemented to provide the error state estimates for the INS. When finished, the GPS and Inertial Navigation system will fuse two navigation systems under different physical principles, GPS and INS, to deliver a stable and accurate navigation solution.