Inertial Navigation aided with GPS information

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Abstract

This work presents a dynamic alignment algorithm for a six-degree of freedom inertial unit. A Differential GPS is used as external sensor. It provides decorrelated range position and doppler velocity information. A simplified error model valid for a local area is also presented. An indirect Kalman Filter approach is used to fuse high frequency inertial information with low frequency GPS data. Experimental results are presented showing that the filter is able to predict high frequency maneuvers as well as detect multipath errors in the GPS information.

1. Introduction

Due to an increasing interest in vehicle automation, particularly in large industries such as mining, applications for integrating and commercialising sensor suites for navigation systems are beginning to present themselves [1-3]. These vehicles will almost certainly require the use of multiple sensors of varying types. To extract the most amount of information from the data, a statistical filter is normally used to estimate the required quantities.
The sensors most commonly used may be broken down into two broad categories: dead reckoning sensors; and external sensors [4]. While dead reckoning sensors tend to be very robust, they do however accumulate error with time. Hence in practice they are periodically reset using information from external sensors. External sensors provide absolute information referenced to the environment, typically by making measurements of prominent known landmarks, whether they be natural or artificial. The external sensors, however, do not tend to be as reliable as dead reckoning sensors, and thus most navigation packages tend to use sensors of both types.
Dead reckoning sensors are further divided into two categories: encoder based; and INS. The inertial sensors make measurements of the internal state of the vehicle. They are typically manufactured in a sealed unit, thus reducing the effect of environmental factors such as dust and water, both of which are highly prevalent in many industrial environments. Only few years ago the application of inertial sensing was limited to high performance-high cost aerospace and maritime applications [5]. However, motivated by the requirements for the automotive industry a whole variety of low cost inertial systems have now become available in diverse applications involving heading and attitude determination [6], [7].
The most common sensors of this type are accelerometers and gyroscopes. Accelerometers measure acceleration with respect to an inertial frame. These accelerations include gravitational and rotational accelerations as well as linear accelerations. Gyroscopes measure the rate of rotation independent of the coordinate frame. A major advantage of inertial sensors is that they are non-radiating and non-jammable and may be packaged and sealed from the environment. This makes them potentially robust in harsh environmental conditions.
A full inertial navigation system (INS) consists of at least three (triaxial) accelerometers and three orthogonal gyroscopes providing acceleration in three dimensions and rotation rates about three axes. In theory, single and double integration of the gyro and accelerometer outputs can give position information. In practice however the non-linearity and noise present in the sensors make this trajectory prediction valid for very short periods of time. An additional external sensor becomes absolutely necessary for resetting purposes. The application of full INS is almost non-existant in commercial land vehicle's applications. The Mechatronic group at the University of Sydney has a standard six-degree of freedom inertial unit that consists of three gyros, three accelerometers and two pendulum gyros. This platform is used to test the alignment algorithm presented in this work.

2. GPS-INS Navigation Loop

The GPS/INS loop uses a full three-dimensional inertial navigation unit as an internal sensor and a differential GPS unit as an external sensor. A brief introduction to these sensors is given and full details of the navigation loop are then presented.

Global Positioning Systems

The Global Positioning System (GPS) is based on 24 satellites circulating in 6 different orbits around the Earth. The system is operated by the US Department of Defence. The orbits and the number of satellites in each orbit have been chosen to assure that at least 5 satellites may be seen at any time from any location on Earth. Each satellite broadcasts its orbital parameter information at very low data rates. These parameters are used by the GPS receiver to predict the future position of the satellites. The measured range to the satellites in view is determined

through a correlation process at approximately 1 kHz. The receiver's position can then be evaluated with at least 4 satellites in view at a much lower frequency, 1-20 Hz, using standard triangulation techniques. Two-dimensional information can be obtained by using the range information from only three satellites. The precision of the solution is affected by two main factors: firstly through the geometry of the actual relative positions of the satellites and receiver, usually referred to as PDOP (position dilution of precision); and secondly, due to the precision in range determination. Errors in range determination are due to atmospheric delays, receiver noise and the errors known as selective availability (SA) that are deliberately introduced by the US Department of Defence. With SA enable, the standard precision of civilian GPS units is in the order of 100 meters.
The precision of GPS can be substantially improved with the use of another station placed at a known fixed location. The implementation is also known as Differential GPS (DGPS). Two main problems still affect DGPS position determination.: satellite availability and multipath signals. The rover needs to see at least three satellites to determine its position in two dimensions. In some cases, buildings or other large equipment may obstruct the signals from one or more of the satellites and hence a position fix can not be generated. Large object can also create multipath signals. The range information is evaluated measuring the travel time of the signal from the satellite to the rover. Sometimes this path may be obstructed but the signal can still reach the rover antenna through an indirect path by reflecting off metal obstacles. This multiple reflection will lead to an erroneous range determination and obviously an incorrect position fix. This problem must be addressed by fusing GPS with another sensor information.

An Ashtech DGPS unit, model G-12, is used. The errors in position determination are of the order of 37 cm CEP, or 95 cm 95% of the time. An additional feature of this receiver is that it can provide position information at a rate of up to 20 Hz, making this unit very appropriate for navigation purposes.

Inertial Navigation Sensors

A full inertial navigation systems (INS) consists of at least three (triaxial) accelerometers and three orthogonal gyroscopes that provide measurements of acceleration in three dimensions and rotation rates about three axes. An INS system assembled from low cost solid-state components is almost always constructed in a "strap-down" configuration. That is all of the gyros and accelerometers are fixed to a common chassis and are not actively controlled on gimbals to align themselves in a pre-specified direction. This design has the advantage of eliminating all moving parts. The strap-down construction however, implies that substantially more complex software is required to compute and distinguish true linear acceleration from angular acceleration and body roll or pitch with respect to gravity. Once true linear acceleration has been determined, vehicle position may be obtained, in principle, by the double integration of the acceleration. Vehicle orientation and attitude may also, in principle, be determined by integration of the rotation rates of the gyros. In practise, this integration leads to unbounded growth in position error with time due to the noise associated with the measurement and the non-linearity of the sensors. Consequently, INS information is useful for determining position and orientation only over short time periods. An INS must be periodically reset by some other absolute position-measuring device, such as, GPS or a position measurement radar system. How long one can rely on INS information to provide a measure of position and orientation depends ultimately on the magnitude of the measurement error or "drift rate".

The INS used was the Watson Inertial Measuring Unit composed of three quartz accelerometers, three vibrating-beam gyros and two pendulum gyros. The information is sampled inside the unit and transmitted serially (RS232) to improve the signal to noise ratio of the measurement.

INS/GPS Navigation Loop Design

A Kalman filter approach is used to fuse the INS and GPS information. The two approaches that are commonly adopted to the problem of fusing information from high- and low-frequency sensors are the total space formulation and the error state space formulation, frequently referred to as direct and indirect filtering. In the direct approach, Figure 1, the position and velocity are part of the states to be estimated and the indicated INS position and velocity are part of the observation with the external sensors. The drawback of this approach is that, in general, high frequency manoeuvres are not usually contemplated in the linear (or linearised) model. The consequence of this omission is that the high frequency information provided by the INS will be unnecessarily attenuated by the filter. The system will not be able to track fast maneuvers.

In the indirect approach, the Kalman filter estimates the errors in position and velocity using the difference between inertial-indicated information and external sensor information. The inertial information can still be obtained even if no additional information is available. This implementation is shown as the indirect feed-forward approach in Figure 2. Here the INS high frequency information propagates through to the output without attenuation and is compensated with low frequency corrections. The INS can also be reset by the filter estimates when external information becomes available. This approach has the potential advantage of including other INS internal parameters in the state vector, such as platform misalignments, gyro and accelerometer bias.

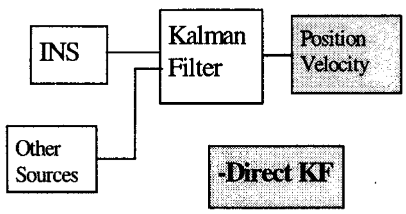

Figure 1. Direct Kalman Filter

The actual implementation proposed for the GPS/INS integration loop is based on the indirect feedback approach and is presented in Figure 2. The indicated position/velocity information derived from the INS is subtracted from the position/velocity provided by the DGPS system. An error propagation model is used to fuse this observation and predict position, velocity, attitude and some other optional parameters to correct the inertial measurement unit. These parameters are fed back to the IMU unit. In this implementation the inertial high frequency information is fed directly to the output without attenuation while the Kalman Filter provides the low frequency correction to the IMU.

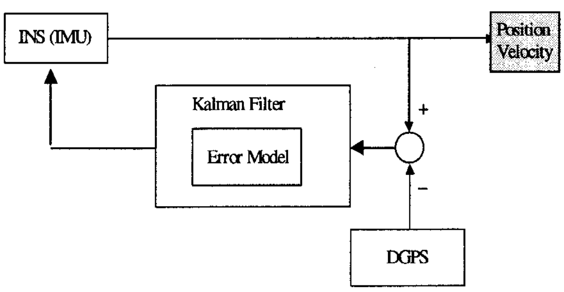

Figure 2: Indirect Kalman Filter

Coordinate Systems and Transformations.

The navigation algorithm is designed in the geographic frame n, with axes $^{n}\{N, E, D\}$, (North, East and Down). It is necessary to determine the transformation from this frame to other frames since the various sensors provide information in different coordinate frames. Figure 3 shows the various coordinate frames involved in this project.

The GPS system provides information in the Earth frame e, with axes $^{e}\{X, Y, Z\}$, which is known as the WGS-84 coordinate frame These axes are fixed to the Earth so that the X and Y axes rotate around the Z axis with the Earth's rotational velocity Ω.

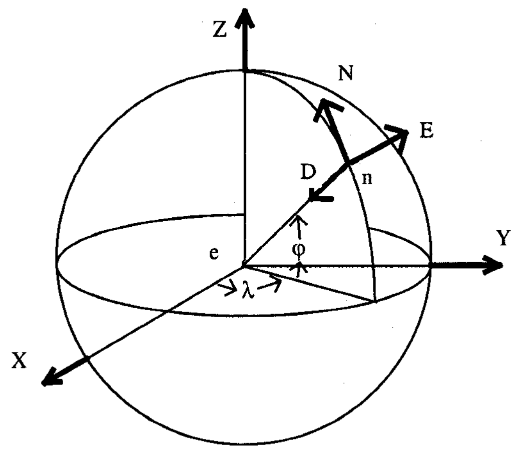

Figure 3 Coordinate systems

WGS-84 to Geodetic

Position information can also be given in Earth frame coordinates but in a polar representation, that is longitude λ, latitude φ and height h, also known as Geodetic coordinate frame. These values can be obtained from x,y and z with the following transformation:

$$
\begin{gathered}
f = 1 - \frac{b}{a} \qquad p = \sqrt{x^2 + y^2} \qquad \theta = \tan^{-1}\left(\frac{za}{pb}\right) \\
ep = \frac{(a^2 - b^2)}{b^2} \qquad e = 2f - f^2 \\
\lambda = a\tan\left(\frac{y}{x}\right) \qquad N = \frac{a}{\sqrt{1 - e\sin^2(\lambda)}} \\
\varphi = \tan^{-1}\left(\frac{2 + ep2 * b\sin^3\theta}{p - e * a\cos^3\theta}\right) \qquad h = \frac{p}{\cos\lambda - N}
\end{gathered} \tag{1}
$$

where a = 6378137 m. and b = 6356752.31m. for WGS-84.

Earth Reference "e" to Local Reference Frame "n"

The transformation from Earth reference "e" to local reference "n" can be evaluated using:

$$
\begin{bmatrix} N \\ E \\ D \end{bmatrix} = \begin{bmatrix} -\sin(\varphi)\cos(\lambda) & -\sin(\varphi)\sin(\lambda) & \cos(\varphi) \\ -\sin(\lambda) & \cos(\lambda) & 0 \\ -\cos(\varphi)\cos(\lambda) & -\cos(\varphi)\sin(\lambda) & -\sin(\varphi) \end{bmatrix} * \begin{bmatrix} x - x_i \\ y - y_i \\ z - z_i \end{bmatrix} \tag{2}
$$

In this case the latitude φ and longitude λ correspond to the origin of the local navigation frame 'n', also designated as x_i, y_i, z_i. The GPS information, which is originally in the Earth coordinate frame, will be transformed to the local navigation frame with equation 2.

Transformation from Body "b" to Local "n" reference frame

The inertial measurement unit will be mounted on the vehicle constituting a new frame. This is called the body frame "b", and has axes ${}^{b}\{R, P, Y\}$, (Roll , Pitch and Yaw). This frame will be in constant rotation with respect to the "n" frame.

The angular velocites of this rotation is measured by three near-orthogonal gyros. The transformation matrix that relates the "b" and "n" coordinate frames is evaluated solving:

$$\dot{C}_b^n = \Omega_{bn} C_b^n \qquad \Omega_{bn} = \begin{bmatrix} 0 & -\omega_Y & \omega_P \\ \omega_Y & 0 & -\omega_R \\ -\omega_P & \omega_R & 0 \end{bmatrix} \quad (3)$$

where Ω_{bn} is the antisymetric velocity matrix and ω_{Is} are the rotation velocities measured by the gyros in the body frame. This integration can be implemented with the following approximation

$$C_b^n(k+1) = C_b^n(I + \Delta\theta)$$

$$\Delta\theta = \begin{bmatrix} 0 & -\Delta\theta_Y & \Delta\theta_P \\ \Delta\theta_Y & 0 & -\Delta\theta_R \\ -\Delta\theta_P & \Delta\theta_R & 0 \end{bmatrix} \quad (4)$$

where $(I+\Delta\theta)$ is the small angle direction cosine matrix relating the frame at time k to the rotating frame at time k+1. This approximation is valid for small angles, which constrains the minimum sampling time of the gyros such that the transformation matrix may be obtained with reasonable accuracy. This sampling time will be a function of the severity of manoeuvres expected from the vehicle. In this application the maximum rotation velocity expected is approximately 25 deg/sec. When sampling at 100 Hz the maximum angle variation will be less than 0.25 degrees.

System Error Model

In order to implement the Kalman Filter proposed ,a model of the propagation of the errors is needed. The dynamics of the Earth surface frame navigator can be described by the following set of equations:

$$\begin{aligned} \dot{R}^n &= V^n \\ \dot{V} &= C_b^n A_{bn}^b + g^n \\ \dot{C}_b^n &= \Omega_{bn}^n C_b^n \end{aligned} \quad (5)$$

The simplify system error model can be written in terms of errors in position R, velocity V and the misalignment angles Φ

$$\begin{bmatrix} \dot{r} \\ \dot{v} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} 0 & I & 0 \\ 0 & 0 & a_n \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} r \\ v \\ \phi \end{bmatrix} + \begin{bmatrix} 0 \\ C_b^n e_a \\ C_b^n e_g \end{bmatrix} \quad \dot{x} = F_g x + Gw \, (6)$$

The biases in the accelerometers and gyros are considered constant during calibration periods. Future models will consider the estimation of these parameters

Observations

The processed acceleration measured by the inertial unit is integrated to obtain velocity and position information as shown in Figure 4.

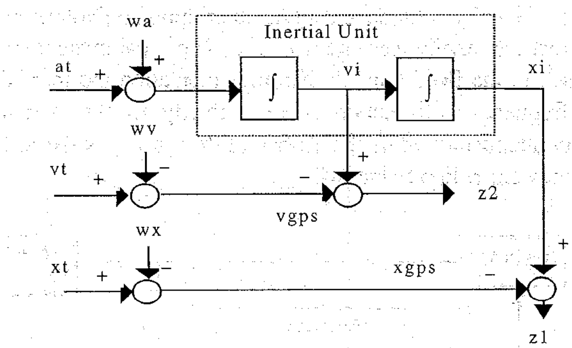

Figure 4 Filter Observations

According to the figure the observation can be written in the following form

$$z(k) = \begin{bmatrix} xi(k) - xgps(k) \\ vi(k) - vgps(k) \end{bmatrix} = \quad (7)$$

$$\begin{bmatrix} [xt(k) + \delta x(k)] - [xt(k) - wx(k)] \\ [vt(k) + \delta v(k)] - [vt(k) - wv(k)] \end{bmatrix} = \begin{bmatrix} \delta x(k) + wx(k) \\ \delta v(k) + wv(k) \end{bmatrix}$$

It can be seen that the observation z is composed of the error in indicated position and velocity plus white noise. Finally, the observation equation for the filter will have the form

$$z = Hx + Dv \quad (8)$$

with

$$H=\begin{bmatrix} I_{3*3} & 0 & 0 \\ 0 & I_{3*3} & 0 \end{bmatrix} \quad v^T=[1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1]$$

Filter Implementation

This section describes the software distribution of the different tasks, the hardware and interconnections required and practical aspects of the filter implementation.

Partition of Navigation Functions

The navigation functions required for the aided INS strapdown system are partitioned between the fast guidance unit and the navigation processor, as shown in Figure 5.

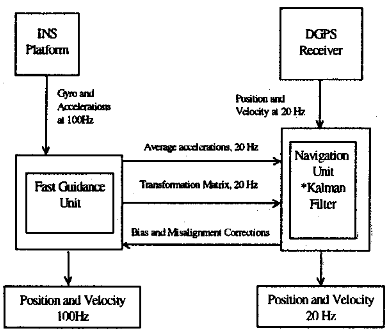

Figure 5: INS/GPS Navigation architecture

The system is implemented on two processors. The first processor is allocated to the fast guidance unit. This processor communicates with the inertial unit through a serial link of 19,200 bit/sec. The inertial measurement unit broadcasts the triaxial gyro and acceleration information at high frequency rate. The guidance unit integrates the direction cosine matrix using the algorithm detailed in equation 4. The acceleration is transmitted together with the transformation matrix to the navigation unit. Although the accelerations are already transformed into the local navigation coordinate frame, the transformation matrix is still required to estimate other parameters. The navigation unit receives position and velocity information from the DGPS receiver at a rate of up to 20 Hz. and process the feedback Kalman Filter fusion algorithm.

Discrete Model

The continuous model of the system is described in equations (6) and (8). The discrete model can be written as

$$\begin{aligned} x(k+1) &= F_d x(k) + Q_d(k) w(k) \\ z(k) &= H_d x(k) + D_d v(k) \end{aligned} \tag{9}$$

Although the system is linear the matrices F and G are time variant. They are mainly functions of the actual acceleration and the transformation matrix C_b^n. The matrices F_d and Q_d need to be evaluated on line for each sampling time. The exact solution of these matrices is out of the question due to the large computational requirement. The following approximation are used to evaluate these matrices:

$$F_d(t_{i+1},t_i) = I + F(t_i)\Delta t + \frac{1}{2} F(t_i) * F(t_i) * \Delta t^2 .$$

$$Q_d(t_i) = G(t_i) Q(t_i) G^T(t_i) \Delta t$$

3. Experimental Results.

The sensors were retrofitted in a Holden Ute vehicle. The car was driven in the neighborhood of the University where buildings and other structures were present obstructing in some cases the direct path of the GPS satellites. Figure 6 shows the trajectory generated by INS alone, (black) and DGPS (grey). It can be seen that the error increased significantly after the first 500 meters. In all the plots DGPS information is drawn in grey while the output of the filter is plotted in black at a much higher frequency. Figure 7 presents the result of DGPS and the filter estimation (black). Figure 8 presents an enlargement after the first turn. In this case the GPS is generating a solution affected by multipaths since the filter is fusing all the GPS data. Fault detection capabilities were included in the run shown in Figure 9. In Figure 10 it can clearly be seen that the fault is detected and the filter navigates with INS alone during the period that the GPS is in fault. There is no noticeable degrading of performance during the GPS fault. Finally in Figure 11, we have the results of disconnecting the GPS after the first 500 meters. It can be seen that the attitude of the unit has been updated properly since the filter is able to predict the trajectory for another 500 meters with small errors.

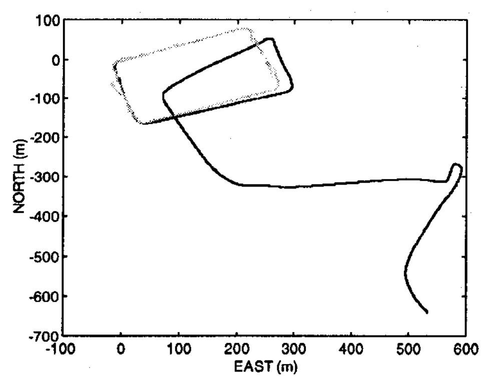

Figure 6. Trajectory without GPS

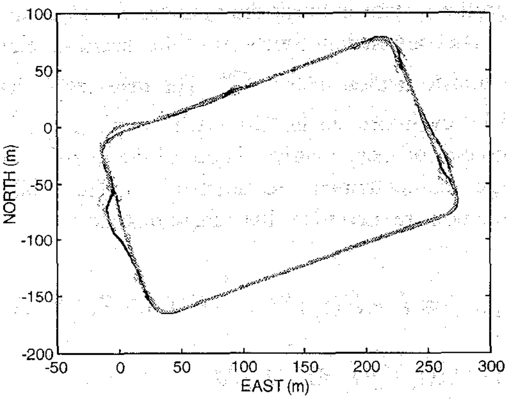

Figure 7. Trajectory with GPS

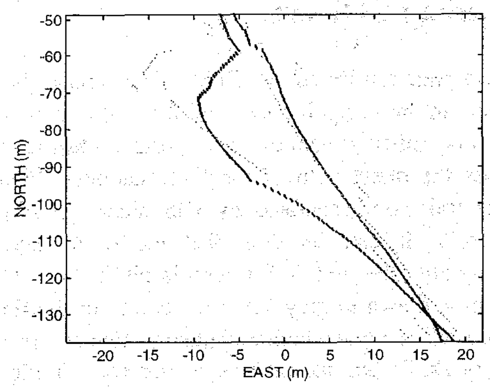

Figure 8. Enhanced Trajectory.

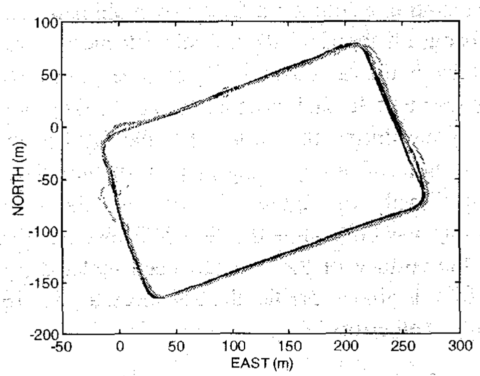

Figure 9. With GPS and Fault Detection

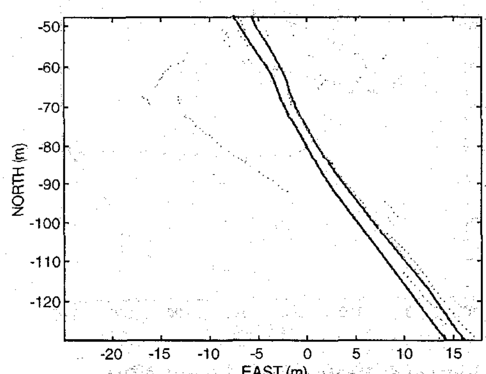

Figure 10. Enhanced GPS and FD

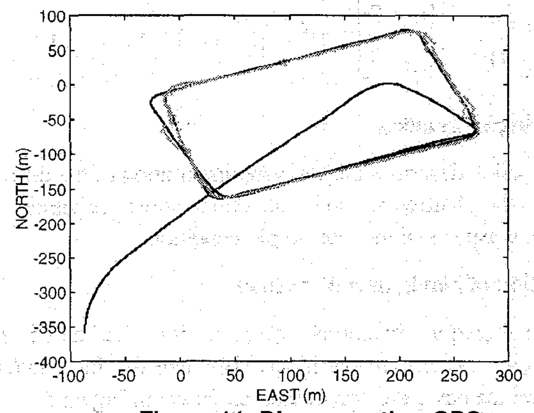

Figure 11. Disconnecting GPS

4. Conclusion

This works presented an alignment algorithm to work with standard INS and DGPS systems. The experimental results have shown that the alignment algorithm is capable of updating the attitude information while the vehicle is moving. Future work will extend the error models to estimate biases in accelerometers and gyros.

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