Inertial Navigation Sensor and GPS integrated for Mobile mapping

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1. Introduction

Raised Pavement Markers (RPMs, Cats eyes), traffic signs and road markings have retro-reflective properties on the roads. Road paint and traffic signs depreciate periodically, whereas RPMs tend to fail without having a fading period. Malfunctioning RPMs are one of many factors that contribute to road traffic accidents (BERG, 2006). Unfortunately detection and mapping of broken or damaged RPMs is difficult on busy motorways. In collaboration with the National Road Authority of Ireland (NRA), research at the Institute of Technology Blanchardstown has resulted in the development of a mobile and portable mapping system that is capable of the identification of RPMs, traffic signs and road markings. Using stereo computer vision techniques, RPMs can be identified in images and their estimated national grid coordinates can be found. The inter-spatial distances between studs can be used to infer the number of defective or missing studs (MULVHILL, 2005).

Earlier versions of the Mobile Mapping System (MCLOUGHLIN, 2005) had adequately high precision with the identification of RPMs positions from vehicle-mounted cameras. This prototype estimated the vehicle/camera location and trajectory using a GPS sensor. Thus the portable mapping system had shortcomings due to the GPS's two main problems, signal obstruction and low refresh rates (KONOSHI, 2000).

An alternative solution was to incorporate strap-down Inertial Navigation Sensors (INS) to obtain the vehicles attitude and velocity at high refresh rate (DOROBANTU, 1999). INS obtains measurements for the rate of turn using a gyroscope and acceleration using an accelerometer. These measurements need to be integrated over time to obtain orientation changes and velocity measurements. The INS components produce small measurement errors that accumulate over time and cause drift errors. Therefore the sensor is accurate over short time intervals but needs to be combined with other devices to obtain stability over long measurement periods. The INS sensors can also be combined with a magnetometer that uses the magnetic north as a reference to stop orientation errors; this is known as an Inertial Measurement Unit (IMU). To limit the errors when calculating trajectories with the INS or an IMU, they can be combined with a GPS device through a complementary filter (RODGERS, 2003).

Techniques are described in the following paper to incorporate GPS with an IMU sensor. A complementary filter known as the Kalman Filter (KF) provides the possibility to integrate values from the two sources whilst minimizing errors to provide an accurate trajectory of the vehicle. The following GPS and IMU data is post-processed by an Extended KF (EKF). Preliminary tests have shown that the use of GPS aided INS approaches in the Mobile Mapping System can provide high bandwidths for the vehicles kinematics and facilitates the generation of three dimensional topographic maps of the road surface.

2. Data Acquisition System

The data acquisition system is located in a vehicle roof box consisting of two cameras, a Global Positioning System (GPS), an Inertial Measurement Unit (IMU) and an interfacing PC (Figure 1). Three-dimensional information of the roadways is obtained with two vehicle-mounted cameras (CMOS FireWire IEEE1394 PixeLink). The vehicle kinematics are obtained by a Garmin GPS and a XSENS IMU sensor. An interfacing PC synchronises the hardware and stores all the data from the devices. This interfacing PC is controlled across a wireless network with an in-car notebook PC. The acquisition software uses the Microsoft Foundation Classes (MFC) for event driven data capture.

Figure 1: Data acquisition system

The two main parts of the GPS/IMU system are:

- An acquisition system that synchronises all the devices and stores the data for post-processing.
- A navigation processing system that integrates the GPS and INS data to find the coordinates of the mobile mapping vehicle over a surveyed road.

3. Strapdown navigation mechanism

The IMU sensor consists of three orthogonal accelerometers, gyroscopes and magnetometers. It can provide computed attitude data along with calibrated sensor kinematics data. An internal sensor fusion algorithm using an Extended Kalman filter compensates for attitude drift by reference to the magnetic north (magnetometers). The table opposite gives a reference of the performance specifications of the IMU (XSENS, 2006). The data stream from the sensor contains the orientation in quaternion form.

The calibrated data contains the accelerations and rates of turn in the three orthogonal axes. The Kalman filter prototype was generated in MATLAB and it uses GPS distance and velocity to correct the drift errors of the INS.

Orientation performance
Dynamic Range: all angles in 3D
Angular Resolution: 0.05° RMS
Static Accuracy: <0.5°
Accuracy (heading): <1.0°
Dynamic Accuracy: 2° RMS
Update Rate: max 120 Hz
Calibrated data performance
Accelerometer
Full scale: ± 17m/s/s(1.7g)
Noise density (units √Hz) 0.001
Rate gyro
Full scale: 17 ± deg/s
Noise density (units √Hz) 0.1

Table 1: XSENS MTI SENSOR

3.1 Attitude and Navigation Equations

The Earth Centered Earth Fixed (ECEF) coordinates are used as a common reference frame between the GPS and IMU. GPS positions are transformed from its output format (WGS84) to the ECEF frame. To track a position the attitude and distance traveled must be known. The attitude must be projected from the ECEF to the navigation frame and is calculated from two rotations. The first rotation, $C_{body}^{navigation}$ (Equation 1), consists of the IMU sensor data in Quaternion form and the second rotation, $C_{ECEF}^{Navigaiton}$ (Equation 2), uses the current tangent plane coordinates. Combining these direction cosine equations gives C_{Body}^{ECEF} (Equation 3), the rotation matrix for the common frame (TITTERTON, 2004).

$$C_{body}^{navigation} = \begin{pmatrix} (a^2+b^2+c^2+d^2) & 2(bc-ad) & 2(bd+ac) \\ 2(bc+ad) & (a^2-b^2+c^2-d^2) & 2(cd+ab) \\ 2(bd-ac) & 2(cd+ab) & (a^2-b^2-c^2+d^2) \end{pmatrix} \quad (1)$$

where the Quaternion vector is $Q_b^n = [a \quad b \quad c \quad d]^T \Rightarrow [q1 \quad q2 \quad q3 \quad q4]^T$

$$C_{ECEF}^{Navigaiton} = \begin{pmatrix} -\sin\phi\cos\lambda & -\sin\phi\sin\lambda & \cos\theta \\ -\sin\lambda & \cos\lambda & 0 \\ -\cos\phi\cos\lambda & -\cos\phi\cos\lambda & -\sin\phi \end{pmatrix}, \quad (2)$$

where ϕ is latitude and λ is longitude

$$C_{body}^{ECEF} = C_{navigation}^{ECEF} C_{body}^{navigation} \qquad (3)$$

The velocity dynamics (Equation 4) use the acceleration forces in the body/sensor frame from the accelerometer, $f^{\,i}$, and take subtracts the centripetal accelerations $\omega_{ie}^{i} \times V$ and gravitation forces. The Cosine matrix $\left(C_{body}^{ECEF}\right)^{-1}$ is used in the projection of the gravity vector to the body frame. The following velocity equation does not take into account Coriolis accelerations, as the effects of the earth's rotations are small over small distances and short times intervals.

$$\dot{v} = f^{\,i} - \omega_{ie}^{i} \times V + C_{ECEF}^{body}.g\,, \qquad (4)$$

Where,

V= Previous velocity vector

$\omega_{ie}^{i\ T}$ = Angular velocities in the gyroscopes

g = Gravity vector

$f^{\,i} =$ Accelerations in the accelerometers

C_{ECEF}^{body} = Cosine matrix, ECEF frame to body frame

The velocity dynamics are in the body frame after applying Equation 4.This velocity must be transformed to the ECEF navigation frame (Equation 5) and then integrated over time (Equation 6) to find the position vector R.

$$V^{ECEF} = C_{body}^{ECEF}.\dot{V}^{body} \qquad (5)$$

$$R(t) = \int_{0}^{t} V.dt + R(0) \qquad (6)$$

3.2 Kalman Filter

The EKF was used for the correction of the position and velocity dynamics of the INS sensor with GPS data. Further reading on Kalman filtering can be found in (WELCH, 2004). The general filter is used to generate the best-estimated state for a system when given a measurement vector and state vector that can justify Equation 7.

$$X(k+1) = A(k)X(k) + w(k)$$
$$Y(k) = CX(k) + v(k) \qquad (7)$$

Where X is the state matrix, Y is the measurement matrix, A is state transfer matrix and C is observation matrix with noise v and w at time k.

The state vector (Equation 8) consists of the positions XYZ in the ECEF frame, velocity NED in ECEF frame, attitude in quaternions and gravity in the *Z* plane. As the navigation formulas are nonlinear, a linearized error form is desired for the Kalman filter algorithm. Using a Taylor series expansion we can make an approximation of the state transition matrix A (RODGERS, 2003).

$$X(k) = [P_X \quad P_Y \quad P_Z \quad V_N \quad V_E \quad V_D \quad Q_a \quad Q_b \quad Q_c \quad Q_d \quad g]^T$$
$$Y(k) = [P_X \quad P_Y \quad P_Z \quad V_N \quad V_E \quad V_D]^T \qquad (8)$$

The EKF uses a five-step iteration process (Figure 2). The measurement update and correction is carried out only when the GPS has a correct and valid signal i.e. it has lock on 4 or more satellites.

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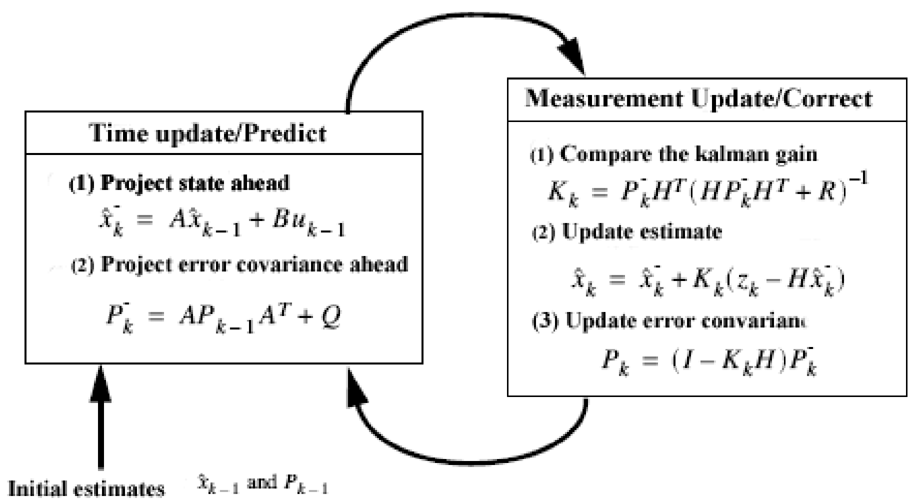

Figure 2: KF block diagram

4. Experimental Results and Conclusion

The experimental test run consisted of a two-kilometre road an urban environment that had numerous roadside trees, surrounding high walls and a roundabout. The GPS lost its position lock regularly. The IMU sensor bandwidth was 100Hz and GPS rate was at 1Hz. The attitude or orientation (Figure 3) had very little noise as it had been directly calibrated from the sensors internal algorithm. The position data (Figure 4) is an observation of the INS positions being aided by the GPS. The GPS position and velocity were only used when it had lock onto four or more satellites. Figure 5 gives a graphical presentation of the results after GPS and IMU have been combined on the road section. Figure 6 shows the more detailed section of the road, where the IMU trajectory is corrected. This type of system can be used at normal road speeds and gives accurate measurements of the road surface to identify safety failures. An ongoing evaluation of the system is taking place on different routes and road conditions. Future work will see the combining of this navigation system with the in-house automated RPMs and road sign vision systems.

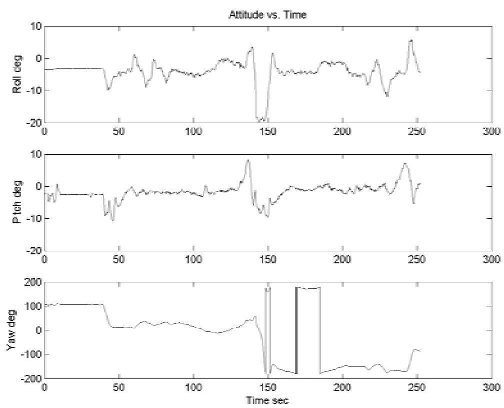

Figure 3: Attitude of the test run

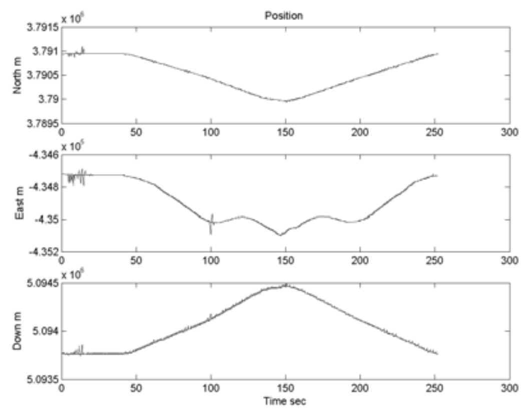

Figure 4: Position filtering

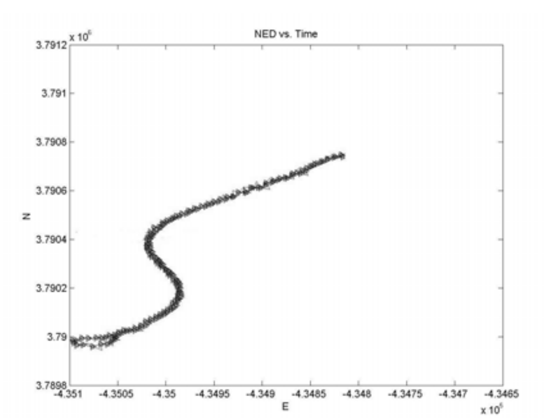

Figure 5: GPS/IMU trajectory path on the test run

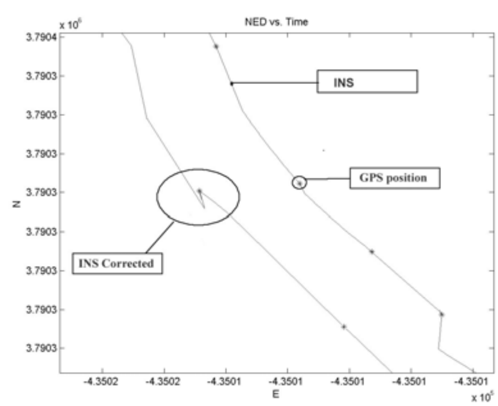

Figure 6: Detailed view of the test run

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Biography

The principle author completed his undergraduate at NUI Maynooth in Computer Science and Software Engineering. His undergraduate research was in the area of spatial mapping of celestial bodies for VTIE (Virtual Telescopes in Education). He is currently doing a research Master in Engineering at ITB in the integration of Inertial Navigation System with a Computer Vision System.