ROAD SIGN SAFETY IDENTIFICATION THROUGH THE USE OF A MOBILE SURVEY SYSTEM

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ABSTRACT:

Techniques are described in the following paper to incorporate a GPS with an IMU sensor to produce more accurate positions and attitude dynamics for geo-reference images of roadways. An Extended Kalman Filter (EKF) provides the possibility to integrate values from the two sources whilst minimizing errors to provide an accurate trajectory of the vehicle. 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 position. The results demonstrate that low cost MEMS IMU/GPS is a feasible solution.

1. INTRODUCTION

1.1 Background

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, Dublin has resulted in the development of a mobile mapping system that is capable of automated identification of RPMs, traffic signs and road markings, see Figure 1, (McLoughlin, 2005).

Figure 1. Road sign detected on road section

A mapping system is made up of two main features, mapping sensors and positioning sensors. The initial approach taken for developing the system was to use stereovision with GPS technologies for road feature detection and mapping. The positioning component assumed planar motion with 3 degrees of freedom. The single antenna GPS provided all positioning parameters ie. Easting, Northings and heading. The heading was obtained through sequential differencing of GPS measurements (Mulvhill, 2006). The system design is low cost, completely portable and can be secured onto any vehicle with a set of roof bars. The vehicle headlights cause retro-reflection on road features. The cameras then record these highlighted features as stereo image pairs.

A standard survey of a road is performed during periods of low ambient lighting. The retro-reflective features are extracted in stereo image pairs by performing image analysis routines. These include techniques such as image thresholding, morphological analysis, photometric analysis and connected component labelling. (McLoughlin, 2006). Corresponding features are identified in the stereo pairs using local correlation based techniques. When corresponding feature points are found, triangulation provides the Euclidean coordinates in the camera frame. When detecting RPMs, the inter-spatial distances between studs was used to infer the number of defective or missing studs that line on the ground plane. Tests have achieved 100% automated detection of defective RPMs and a detection of 94% of road signs.

1.2 Problem outline

The earlier versions of this mobile mapping system had moderate accuracy and precision. Unfortunately both, attitude and positioning power were lost due to the inability to accurately calculate them from the GPS measurements exclusively. The single antenna GPS had shortcomings due to two main problems; signal obstruction and its low refresh rates (Konoshi, 2000). This effected the computed vehicles-camera absolute geographical location and trajectory. The positioning system inadequacies lead to the development of an improved vehicle positioning system as described in this paper.

The alternative solution was to incorporate a strap-down Inertial Measurement Unit (IMU) with a GPS receiver to obtain the vehicles attitude and velocity at high refresh rate. This procedure has been performed many times before and there is a large database of knowledge on this topic (Dorobantu, 1999). IMU 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 IMU components produce small measurement errors that accumulate over time and cause drift errors. As a result the sensor is accurate over short time intervals but needs to be combined with other devices to obtain stability over long measurement periods. The IMU sensors can also be combined with a magnetometer that uses the magnetic north as a reference to stop orientation errors. The IMU that was used for this project was a low cost MEM IMU from XSENS. The inertial unit has an additional 3 axis magnetometer with an on board digital signal processing unit. This processing unit contains a closely coupled KF-based algorithm to provide stable attitude and heading reference (AHRS) data, along with calibrated acceleration, angular rate and magnetic field data.

The outline of the paper is as follows. Section 2 gives a brief overview of the entire data-capturing system and data-capturing algorithm, with particular emphasis on the positioning system. Section 3 gives an overview of the inertial equations and filtering procedures. The final sections give an indication of the preliminary results and conclusions.

2. DATA ACQUISITION SYSTEM

System Hardware

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 observations of the roadways are obtained with two vehicle-mounted cameras (CMOS IEEE1394). A Garmin GPS and a XSENS IMU sensor obtain the vehicle kinematics. The interfacing PC is a Sony portable laptop. This interfacing PC is controlled across a wireless network with another in-car laptop.

Figure 2. Data acquisition system

Synchronisation of the sensors is an important issue. The cameras capturing frequency is triggered using hardware around the GPS 1 Hz pulses while the GPS and IMU synchronisation is software based. The XSENS sensor can give calibrated data at a selectable 25Hz to 120Hz. The synchronisation of the devices is done using a sequence counter variable and this value is shared through inter-process communication. The sequence counter is appended to both GPS and IMU data being logged. Assuming that IMU and GPS internal sampling frequencies are stable and all the data is logged the maximum timing offset error is <(GPS sample frequency/IMU sample frequency).

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 and attitude of the mobile mapping vehicle over a surveyed road.

3. STRAPDOWN NAVIGATION MECHANISM

The Xsens IMU sensor consists of three orthogonal accelerometers, gyroscopes and magnetometers. Table 1 below gives a reference of the performance specifications of the IMU (Xsens, 2006). The IMU can provide computed attitude data along with calibrated sensor kinematics data. The following section will show inertial navigation equations. These equations are based on Newton’s laws of motion, which can calculate the vehicles acceleration with the inertial data. The accelerations can be integrated over time for velocity and positions measurements. A sensor fusion algorithm uses an Extended Kalman Filter to compensate for errors in the inertial calculations with GPS data.

Performance Data	Values
Orientations	
Dynamic Range	3D
Angular Resolution	0.05° RMS
Static Accuracy	<1.0°
Accuracy (heading)	2° RMS
Calibrated	
-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 specification

3.1 Attitude and Navigation Equations

The Earth Centred Earth Fixed (ECEF) coordinates are used as a common reference frame between the GPS and IMU. GPS positions and velocities are in the ECEF frame. To track a position the attitude and distance travelled must be known. The attitude projections needed are from the body frame to the ECEF and are 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 a, b, c, d= Quaternion units

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

where ϕ = latitude
λ = longitude

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

The velocity dynamics (Equation 4) use the acceleration forces in the body/sensor frame from the accelerometer, f^i, and subtracts the centripetal accelerations $\omega_{en}^i \times V$ and gravitation forces. The Cosine matrix C_{ECEF}^{body} 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.

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

where V = previous velocity vector

ω_{en}^i = angular velocities of body frame

g = gravity vector

f^i = accelerations of body frame

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.

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

$$R(t) = \int_0^t V.dt + R(0) \quad (6)$$

3.2 Kalman filtering

The EKF was used for the correction of the position and velocity dynamics of the INS sensor with GPS data. Further reading on the Kalman filtering can be found in (Welch, 2004). The Kalman state vector contains absolute position, velocity, attitude and gravity calculations. The state vector consists of the positions XYZ in the ECEF frame, velocity NED in ECEF frame, attitude in Quaternion form and gravity vector bias. Due to the non-linear nature of the navigation formulas, a Linearized error form is desired for the Kalman filter algorithm. Using a first order Taylor series expansion, we can make an approximation for the state transition matrix (Rodgers, 2003).

There are six observations used to update the Kalman filter; three-dimensional position in the ECEF frame and three-dimensional velocity also in the ECEF frame. The position observations are the relative differences between the INS and GPS positions (Equation 7). The velocity errors are calculated from the difference between the INS and GPS calculated velocities (Equation 8).

$$r_{IMU} - r_{GPS} = \delta r + n \quad (7)$$

$$v_{IMU} - v_{GPS} = \delta v + n \quad (8)$$

where r = position vector
δr = position error
v = velocity vector
δv = velocity error
n = white noise

3.3 Experimental evaluation

The initial testing of the GPS aided INS algorithm was done using simulated data. The preliminary commissioning test for accessing the quality of the positioning system was conducted in a road environment.

3.3.1 Test descriptions: Field tests with the data acquisition hardware were carried out on a 22-kilometre stretch of M4 motorway, located west of Dublin, Ireland. The selected section of motorway had the suitable test case scenario, straight and curved sections with smooth changes in altitudes as seen in Figure 3. Both sides of the motorway were traversed using a large intersection roundabout to turn. The test run was conducted at motorway speeds of 120km/h with average speed for test being 62 km/h. When observing the figures it is worth taking note that driving is on the left side in Ireland.

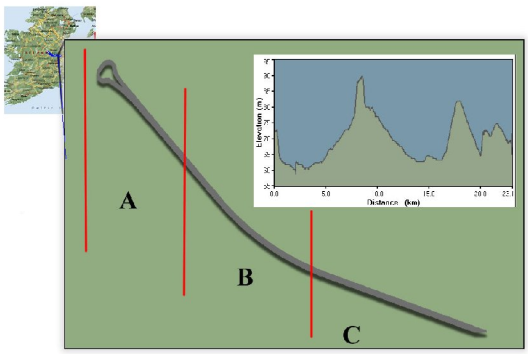

Figure 3. Map of test cases

The test consisted of using the GPS and IMU mounted on the roof of a vehicle. The primary GPS was a Garmin street pilot III+ and a second GPS sensor was also used (GARMIN Etrex with WAAS/EGNOS enabled). Only one set of GPS data was used for direct integration of GPS/IMU while the second was an additional accuracy reference. Data was logged at 1HZ from both GPS sensors and 25HZ from the IMU.

3.3.2 Evaluation of data logging: The use of software events allowed for more accurate data logs and higher synchronised data. This is advantageous over software polling, as priority of the polling thread cannot always be guaranteed on MS Windows environments. In the static environment, the logged data reported minor omissions but on field-tests, logs had omissions caused by vibration and shock to the interfacing PC and the other devices. Table 2 gives an average of logged data while conducting this field run against a previous version of the capture software that used hardware polling.

Setting	% Data Captured
Polling GPS 1Hz	100
Events GPS 1Hz	100
Polling IMU 25Hz	>91.7
Events IMU 25Hz	>98.99

Table 2. GPS/IMU logs over 20 minute averages

3.3.3 Types of logged data: The data recorded from the IMU consisted of the two log files containing, orientation, accelerometer and gyroscope data for the 3 axes of the vehicle. Figure 4 shows orientation data for the test run with slight adjustments in the yaw angle for North turn. Xsens, the manufactures of the IMU, supply magnetic field mapping software. The mapping vehicle contains ferromagnetic materials, which can cause disturbances in the IMU magnetometers. The calibration software results give a calibration summary with an advanced quality indicator and an estimated accuracy of orientation. On this test run the reporting calibration accuracy was <1.2 degrees for orientation.

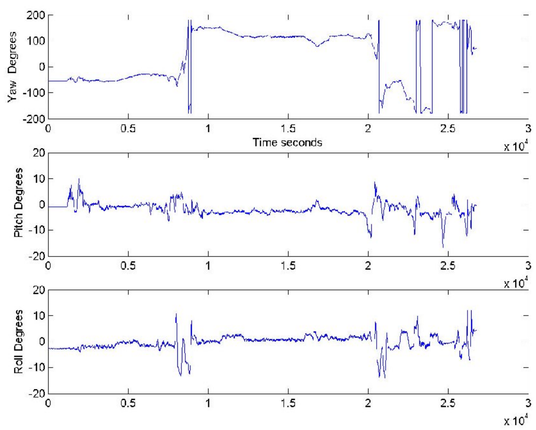

Figure 4. AHRS Orientation over test

The main information obtained from the GPS devices was positions, velocities and a measurement of the position accuracy. Data logged off the GPS devices were in simple text output protocol. The GPS observation quality was based on Horizontal Position Error (HPE), which is a calculation based on a number of factors such as dilution of precision and signal quality. The mean position errors were 3.654 meters with the primary GPS and the second GPS had a mean error of 3.04 meter. The quality of trajectory differences can be easily observed in the figures that follow.

3.4 Results after Kalman Filtering

The data was first filtered using the primary GPS to aid the inertial data and the second GPS was used as a reference for the quality of the filter algorithm. The procedure was then changed with the second GPS being used in the filter. The standard deviations for KF updates were obtained through empirical analysis and categorized for different scenarios. The filter updates were carried out with GPS observation <5 meters with the primary GPS and <4 meters with the second GPS device. Figure 5 gives an observation of the filtered 3 axes positions in the ECEF frame.

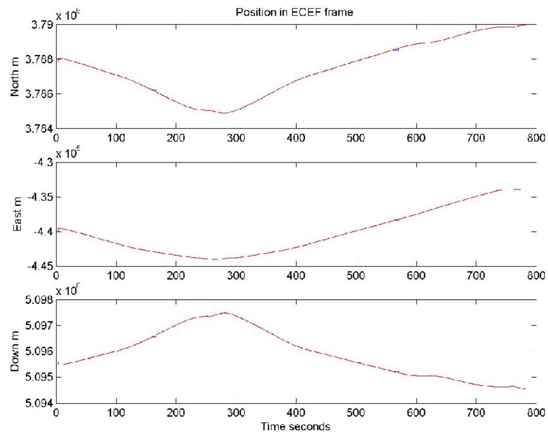

Figure 5. KM filter positions in the ECEF Frame

A section of the road had a bridge that caused signal disruptions. As the errors were large in the GPS, the filter did not use updates and so used only inertial data to bridge the errors in the GPS. Over 154 meters of signal bridging occurred with a 15.5 meter error distributed exponentially.

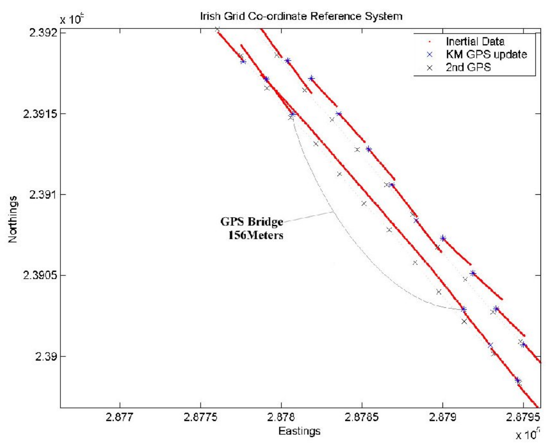

Figure 6. Primary GPS with satellite error (Road Section B)

The primary GPS exhibited poor positioning while travelling at slow speeds. These large position errors caused a rough roundabout trajectory as seen in Figure 7. In Figure 8 a more accurate estimation can be seen by the system when using the second GPS for position updates as the filter has a large dependence on the GPS observations.

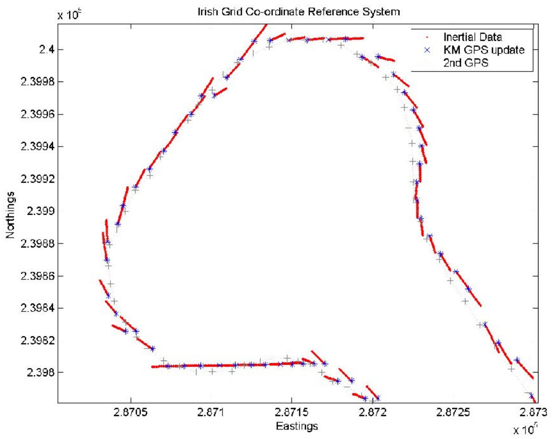

Figure 7. EKF with updates from primary GPS

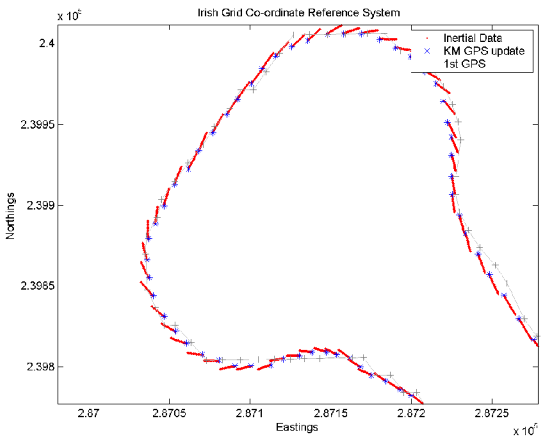

Figure 8. EKF with second GPS Receiver

The best trajectory can be seen at sections B and C on the map. The steady smooth change in turn and straight produced accurate observations. Figure 8 shows filtered data with a standard deviation of 0.2 meters for the covariance matrix, R, on both sides of the motorway.

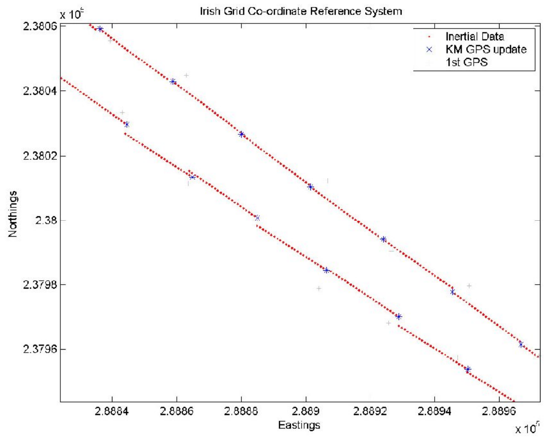

Figure 9. Section B EKF updates from second GPS receiver

4. FUTHURE WORK AND CONCLUSION

During initial commissioning the IMU capture was at a mere 25 Hz. Increasing this up to its maximum of 120 Hz should yield more accurate results. Without additional enhancements the system is highly dependent on the GPS observations as seen in the results. The Kalman covariance matrixes are set to velocities and positions that highly thrust the GPS estimates. The preliminary results conclude that the inertial data with the GPS sensor can provide the higher frequency of position along with orientation data. Future work will see more extensive, statistical analysis of the errors, with positions being modelled in the local grid coordinate system rather that the ECEF frame. Nonholonomic constraints and the subtraction of Coriolis terms can also be applied to the navigation equations to help in the reduction of error.

This paper has presented an overview of a currently low cost IMU combined with low cost GPS. This simple and effective navigation solution provides the assessment of the kinematics and positioning of the vehicle, which is needed by the previously built computer vision application.

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