Performance of GPS and Low-cost INS Integration in Marine Surveying

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Abstract

The Global Positioning System (GPS) and Inertial Navigation Systems (INS) are increasingly being integrated to obtain robust position and attitude determination solutions. Over the past few years, a number of low cost inertial sensors have come on the market. This article demonstrates the potential performance of an integrated GPS and low cost INS for marine navigation and surveying. It is demonstrated that integrating a low cost INS with a single GPS antenna does not provide the accuracies required. However, using two GPS antennas, such an integrated system can meet marine surveying requirements.

Résumé

Le Système global de positionnement (GPS) et les Systèmes de navigation par inertie (INS) sont de plus en plus unifiés afin d'obtenir des solutions robustes en matière de détermination de la position et de l'orientation. Au cours des années passées, un certain nombre de capteurs inertiels à faible coût ont été mis sur le marché. Cet article démontre les performances potentielles d'un GPS intégré et des INS à faible coût pour la navigation maritime et l'hydrographie. Il est démontré que l'intégration d'un INS à faible coût avec une seule antenne GPS ne permet pas d'obtenir la précision requise. Néanmoins en utilisant deux antennes GPS , ce système intégré peut répondre aux exigences maritimes en matière d'hydrographie.

Resumen

Los Sistemas de Posicionamiento Global (GPS) y los Sistemas de Navegación Inercial (INS) están integrándose cada vez más, para obtener una posición robusta y soluciones para determinar las actitudes. Durante los pasados años, un número de sensores inerciales de bajo coste han llegado al mercado. Este artículo demuestra el funcionamiento potencial de una integración de GPS e INS de bajo coste para la navegación marina y levantamientos. Ha quedado demostrado que el integrar una INS de bajo coste con una antena GPS no proporciona las precisiones requeridas. Sin embargo al utilizar un sistema de dos antenas GPS dicho sistema puede cumplir los requerimientos de los levantamientos marinos.

GPS and INS integrated systems are increasingly being used for position and attitude determination for a broad variety of applications. It is well known that GPS and INS sensors have complementary characteristics that when combined, provide robust and accurate navigation. The basic principle is that GPS can provide position and velocity at relatively low data rates (approximately 1-10Hz). The accuracy of such a positioning solution depends on the type of receiver and the operating mode, but GPS provides a position solution that does not degrade over time. The primary limitation of GPS is that it only works when there is a clear view of the sky allowing measurements to four or more satellites. An INS, on the other hand, will output position, velocity and attitude at a high data rate with no need for external measurements. An INS generally has good short-term navigation performance that drifts over time. The rate of the drift is directly related to the quality of the inertial components. When INS and GPS are combined, a drift free, high accuracy, high rate navigation solution is obtained. In addition, when gaps in the GPS data occur, the INS can be used to bridge these periods.

The primary factor that restricts the use of GPS and INS for a broader range of applications is the current high cost of the inertial components. The inertial components usually comprise of three orthogonally mounted accelerometers and gyros to form an Inertial Measurement Unit (IMU). Over the past few years, a number of low cost inertial sensor assemblies have come on the market. These are typically constructed using Micro-machined Electro Mechanical Sensors (MEMS) which are low cost and can be batch fabricated. MEMS also have the advantage that there are no moving parts such as bearings that wear over time. Other advantages offered by MEMS are that they require low power and have good reliability. Unfortunately, MEMS typically offer much lower accuracy than other inertial technologies such as Fibre Optic Gyros (FOG) and Ring Laser Gyros (RLG). MEMS also typically experience large bias and scale factor errors which are often highly temperature dependent. Although there have been significant advances in MEMS technologies (see Schmidt (2003) and Barbour (2003)), low cost MEMS IMUs have to be integrated with some kind of aiding sensor if they are to be used successfully in navigation applications. Typically this is achieved using position and velocity updates from a GPS receiver (see, for example, Scherzinger (2000) and Wolf (1997)).

The marine environment is one area where the benefit of integrating GPS with lower cost inertial sensors is yet to be fully exploited. Current commercial GPS/INS systems are usually based around so called 'tactical grade' inertial components (due to their use in defence applications). The inertial components are usually the largest single cost of any of the components in the integrated system. A typical attitude accuracy required for a modern multibeam sonar with a swath width of 150° is 0.05° in the roll axis, with a similar requirement for pitch and heading (Trethewey et al., 1999). This results in a depth error of 0.5% at the largest scan angle. The focus of this article is whether a GPS and low cost INS system can meet the 0.05° requirement. It is demonstrated that these requirements cannot be met using a low cost IMU integrated with a single antenna GPS receiver. However, using two GPS antennas in order to derive a heading observation, these accuracies can nearly be achieved.

This paper also examines the construction, installation and results from an integrated GPS and low cost INS system built from Commercial Off-The-Shelf (COTS) components for a marine surveying application. A marine trial was undertaken off Plymouth, UK, which compared the attitude solution from a GPS and low cost INS system with a commercial GPS/INS system using a tactical grade INS. The GPS and low cost INS system was constructed using COTS components. These were dual frequency Ashtech GPS receivers; a Crossbow MEMS IMU; a notebook PC used for data logging; and integration software developed by the University of Nottingham. The advantage of using COTS components is that the system can be configured for different applications and can utilise existing equipment that may already be installed in the vessel. The system can also be configured for real-time operation, with high accuracy synchronisation between the inertial sensor and the GPS measurements achieved without using specialist hardware.

Marine Trial

A marine trial was conducted in February 2002 off Plymouth, UK to test the position and attitude accuracy of a typical MEMS IMU integrated with GPS. The trial was conducted on the River Tamar in Plymouth, UK using a small hydrographic survey vessel owned by the Royal Naval Hydrographic

School, *HMS Drake*. The survey vessel was used since it has a GPS/INS system installed which is used for geo-referencing the multibeam sonar mounted on the underside of the vessel. The GPS/INS system installed is the Applanix Position and Orientation Sensor for Marine Vessels (POS/MV) 320, supplied by TSS (UK) Ltd. The POS/MV system was used to provide an attitude reference to compare the solution obtained using a lower performance IMU.

The POS/MV 320 system is based around a tactical grade Litton LN200 IMU which is constructed using three orthogonally mounted silicon accelerometers and fibre optic gyros. The gyros are specified as 1 deg/h drift, which are typically classified as tactical grade. In addition to the IMU, two antennas connected to dual frequency Novatel GPS receivers are mounted to the roof of the survey vessel with an antenna separation of approximately 2 metres. The two receivers form what Applanix call the GPS Azimuth Measurement Subsystem (GAMS). The two GPS receivers are used to address a problem that occurs in the marine environment when the vessel undergoes long periods of low dynamics. Not all of the INS errors can be estimated through position and velocity updates when the vehicle in which the system is installed is either static, or at constant velocity. One such error is the heading error. Take, for example, the situation when the IMU is static and level. If the heading is in error, a position error will not occur unless the IMU moves in a horizontal direction (as soon as the IMU moves, the attitude is used to compute which way the axes are aligned). This problem is referred to as observability; when the INS is static, the heading error is said to be unobservable. When there are long periods of low horizontal acceleration in marine applications, some form of external heading reference is required to stop the INS heading drift.

The POS/MV system uses GAMS in order to maintain the heading accuracy during periods of low horizontal acceleration. The system utilises GPS carrier phase measurements in order to determine a GPS-only heading estimate to approximately 0.1-0.5° depending on baseline separation and the level of multipath (TSS (UK) Ltd, 1999). Accurate estimates of attitude can be obtained from the GPS signals because the antennas are located close together and hence experience the same atmospheric delays as the signal passes through the atmosphere. Hence, the primary error source for GPS attitude estimation is multipath. The heading estimate from the GPS phase measurements is noisy but is free of drift which makes it ideal to use as an extra observation for an integration Kalman filter.

The specification of the integrated POS/MV solution is given in Table 1. The table shows that the POS/MV system can work in either standalone or differential mode. The position accuracy obtained from the integrated system is typically the same accuracy as that provided by a GPS-only solution. This is principally due to atmospheric errors dominating the positioning errors in a GPS system. The table also shows that the attitude errors are independent of the position accuracy provided by the GPS. The roll and pitch errors are significantly better than the heading accuracy due to the observability problem mentioned above. The heading accuracy is dependent on a combination of vessel dynamics, and the level of multipath experienced by the GPS receivers. This is because multipath dominates the error budget for obtaining attitude from GPS range measurements. The table shows that without using GPS attitude aiding, the heading errors can be significantly larger.

	GPS position type		
	C/A	DGPS	RTK
Horizontal Position (m) CEP	15-40	0.5-4	0.04-0.1
Velocity (ms^{-1})	0.5	0.03	<0.03
Roll and pitch (°) RMS	0.02	0.02	0.02
Heading with GAMS (°) RMS	0.02-0.1	0.02-0.1	0.02-0.1
Heading without GAMS (°) RMS	0.02-2	0.02-2	0.02-2

Table 1: POS/MV 320 specification (TSS UK Ltd, 1999)

COTS IMU

There are generally four categories that are used to class various grades of gyro and accelerometer technologies. These are *navigation, tactical, low* *cost* and *automotive* grades. Navigation grade performance typically refers to an IMU that can be used as a sole means of navigation without the requirement for updates from an external positioning sensor such as GPS. Such IMUs are typically very expensive (>US$ 100k) but are capable of standalone navigation performance of approximately 1 nautical mile per hour. Tactical grade refers to military applications where the IMU is required to produce position solutions for only a short period of time. Such sensors usually cost approximately $20k, although costs are constantly decreasing as more applications are found. Low cost sensors typically refer to IMUs that cost approximately US$ 1k - US$ 10k, although again, such costs are rapidly decreasing. The low cost sensors generally have to be integrated with some form of aiding sensor in order to allow the user to obtain any kind of useful navigation solution. Most navigation, tactical and low-cost grade sensors have strict export licenses that must be obtained during purchase. Finally, automotive grade refers to inertial sensors that are very low cost (in the order of tens of dollars). The term automotive refers to the sensors typically being used in motor vehicles for example, for Anti-lock Braking Systems (ABS) and triggering air bags. Such automotive grade sensors are currently not able to meet the requirements for navigation and surveying applications. Typical examples of the performance obtained from navigation, tactical and low cost sensors is given in Table 2.

Grade	Navigation	Tactical	Low Cost
Example	Honeywell HG9900[1]	Litton LN200[2]	Crossbow AHRS-DMU-HDX 400CA[3]
Dimensions (cm)	14.0x16.3x13.6	8.9x8.9x8.5	7.6x9.5x10.4
Gyro	Ring Laser	Fibre Optic	MEMS
Bias (°/h)	<0.003	1-10	<3600
Scale Factor (ppm)	<5	100	<10000
Noise (°/h/√Hz)	<0.002	0.04-0.1	<0.85
Accelerometer	Quartz	Silicon	Silicon
Bias	<25μg	200μg-1mg	< ±30mg
Scale factor (ppm)	<100	300	<10000
Noise	-	50μg/√Hz	<0.15 m/s/√Hz

Table 2: Strapdown IMU error characteristics [1]Honeywell (2004), [2]Northrup Gruman (2004), [3]Crossbow Technology Inc (2000)

There is also a significant amount of ongoing research in developing MEMS themselves to reach higher accuracy's for lower cost. See, for example, Green (2004) and Hanse (2004). The most significant advances in MEMS technology however, have been in developing gyros. The current aim of MEMS manufacturers is to reach 1 degree per hour performance, which is a similar performance to the lower cost RLG and FOG systems. An added advantage of obtaining 1deg/h performance is that the gyro is sensitive enough to measure the turn rate of the Earth which is 15deg/h. By measuring the turn rate of the Earth, the gyro can be used without an external aiding sensor to obtain an initial heading. Some sensor designers even foresee that by 2010, it will be possible to obtain navigation performance of 0.01deg/h using a MEMS IMU only 2in^3 in size (Schmidt, 2003).

The focus of this paper is the performance that is achievable from sensors that are currently available. Of course, future developments in inertial sensors will reduce costs allowing GPS and INS technology to filter into wider application areas. For the trial, a low cost MEMS IMU was used. The sensor that was selected was a Crossbow AHRS-DMU-HDX 400CA which is owned by the University of Nottingham. The Crossbow sensor is a COTS sensor that is designed to be used as an Attitude and Heading Reference System (AHRS). The specification of the sensor is given in Table 2. The Crossbow AHRS contains three orthogonal gyros, accelerometers and magnetometers that are used to compute a standalone attitude solution. AHRS sensors are primarily intended for applications such as UAVs, avionics and platform stabilisation (Crossbow Technology Inc., 2000). The problem with AHRS is that the attitude errors can be significant when high vehicle dynamics or magnetic disturbances are present. In this trial, the Crossbow sensor is used as a conventional IMU where only the raw output of the gyros and accelerometers is used. The specification of the gyro and accelerometers is at the lower end of MEMS, as the Crossbow is an early revision compared to the version that is currently available. The sensor used can now be considered as providing similar sensor specification to current sensors that cost approximately US$ 5k.

The Crossbow IMU provides three modes of operation: *voltage, scaled* and *angle* mode. In voltage mode, the AHRS sensor uses the internal Analogue to Digital (A-D) converter to sample the accelerometers and gyros, and outputs the raw voltages over a serial interface at approximately 163Hz. In scaled sensor mode, the AHRS compensates the raw measurements using internally estimated calibration coefficients. The scaled measurements are available over the serial interface at approximately 100Hz. Angle mode operates at 70Hz and is used for when the sensor is required to operate as an AHRS. For the marine trial, the sensor was operated in voltage mode so that it was functioning purely as a low cost IMU.

Sensor Synchronisation

A very important issue in the configuration of any COTS GPS and INS integrated system is the synchronisation of the sensors. It is necessary to time tag the INS measurements to a high accuracy, so that the position and velocity is differenced at the same time when it is used to update the integration Kalman filter. The issue of time tagging the INS measurements with an accurate time stamp is rarely addressed by the manufacturers of COTS IMUs so it is up to the user to provide the time synchronisation (which is a non-trivial task).

There are commonly two methods in which the IMU data is made available: analogue and digital. The Crossbow IMU provides both methods for collecting the data. At the University of Nottingham, several pieces of software are available for collecting data from various COTS IMUs. For the marine trial, it was decided that the analogue output of the sensor would be sampled using an Analogue to Digital (A-D) converter card. The card used was an ADAC PCM-5516-16, which plugs into the PCMCIA slot on a standard notebook PC. The A-D card was configured so that as the samples were collected, a pulse was sent regularly to the GPS receiver. The GPS receiver logs the time of the pulse using the event marker input and the logged times are then used to compute all of the time stamps for each sample of IMU data.

Unfortunately, when the Plymouth trial took place, the Ashtech Z-XII receivers that were used had recently been upgraded to a new firmware version. As a result, the event marker input failed which meant that the Crossbow IMU data was not time stamped. Consequently, a cross-correlation technique was used to match the Crossbow IMU data with the raw IMU data from the POS/MV IMU. This could be achieved because the POS/MV data is accurately time stamped by the Applanix POS Computer System. The cross correlation function computes the correlation between two data sets. The Crossbow IMU data was first coarsely time stamped using the time at which the IMU data collection began. Different time offsets were then applied to the Crossbow data, and the cross correlation was computed at many different points throughout the dataset. The time offset that corresponded to the maximum cross correlation was then identified as the correct time. Linear regression was used to remove the drift profile that resulted from the Crossbow data. Further details of the cross correlation method can be found in Hide (2003).

The cross correlation method is suitable to use with the marine data set because of the movement of the vessel on the water as there is always some low frequency motion in the output of the inertial sensors. This technique is likely to be less effective for trajectories with less movement such as those obtained from land vehicles. The standard deviation of the final cross correlation of the IMU records was computed to be less than 6.5ms. Since the Plymouth marine trial was conducted, an extensive range of data collection software has been developed at the University of Nottingham for collecting analogue and digital data from a range of COTS IMUs using either the ADAC A-D PCMCIA board, or serial data.

GPS and INS Integration Software

To integrate the GPS and INS data, software developed at the University of Nottingham called KinPos^{i} was used. KinPos^{i} can be configured to provide different GPS and INS integration algorithms that provide a range of integration levels. The simplest mode of operation is depicted in Figure 1. The figure shows how GPS measurements are used to correct the INS. Firstly the raw turn rates and accelerations from the IMU are sampled at a high data rate (typically 200Hz). These raw measurements are transformed to estimates of position, velocity and attitude using strapdown mechanisation equations. The INS mechanisation equations are computed at the data rate of the IMU so that a navigation solution can be output at a high data rate if required. In addition, the INS will give a navigation solution even if there is not a GPS update available.

The bottom three steps of Figure 1 show that the raw GPS data is sampled by the GPS receiver and is pre-processed to form observations for a GPS-only Kalman filter. The GPS Kalman filter is used to provide a smooth estimate of the position and velocity of the GPS antenna. These three steps can be performed in the GPS hardware, but in this instance, the raw data was logged to a file so it could be processed using the GPS algorithms provided by KinPos^i. Although KinPos^i was used to post-process the GPS and INS data, all of the algorithms can be used in a real-time system so that the results documented in this paper can be achieved in a real-time system.

The GPS position and velocity estimates are differenced with the INS estimates of position and velocity to form observations for an integration Kalman filter. The integration Kalman filter estimates position, velocity and attitude errors for the INS, and also the gyro and accelerometer bias errors. This integration approach is called decentralised filtering because the GPS measurements are processed in a separate Kalman filter to the integration filter. KinPos^i can also integrate the data using the centralised filtering structure where the GPS-only Kalman filter is removed and the data is combined in a single filter. Using this approach, the inertial data is used to estimate carrier phase ambiguities, and can also use GPS measurements, even when there are less than four satellites available. This filtering structure was not used for the Plymouth marine trial because there were always more than 6 satellites available throughout the trial, and the initial carrier phase ambiguities were resolved within the first three seconds.

Marine Trial Sensor Configuration

The sensor configuration for the marine trial is depicted by Figure 2. The POS/MV system is permanently installed in the survey vessel with the two GPS antennas for the POS/MV rigidly mounted to the roof of the vessel. The POS/MV processor is rack mounted in the main cabin with a notebook computer used to control and log the data from the POS/MV. The IMU for the POS/MV is located on the floor of the front cabin. The low cost Crossbow IMU was also mounted on the floor of the front cabin so that the attitude solution could be compared directly to the POS/MV solution.

Three dual frequency Ashtech ZX-II receivers were connected to three Ashtech choke ring antennas which were rigidly attached to a wooden frame at the front of the vessel. Three antennas were

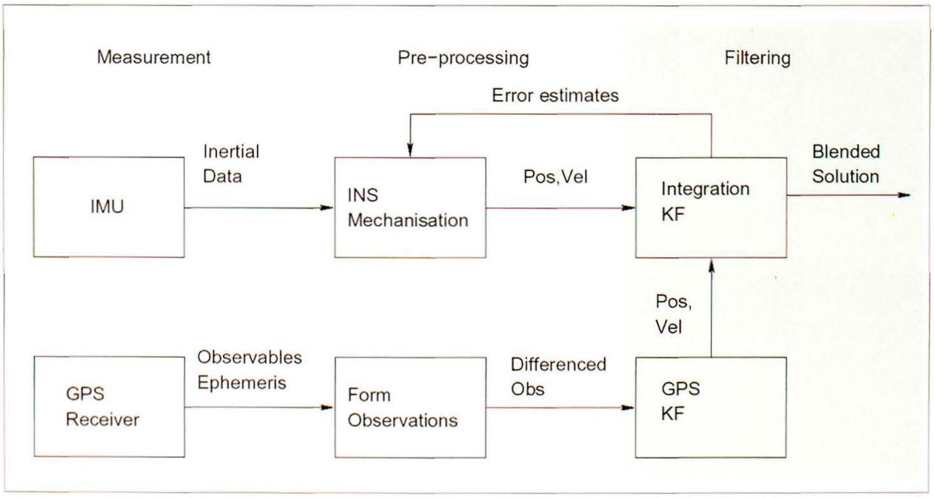

Figure 1: Decentralised Kalman filter

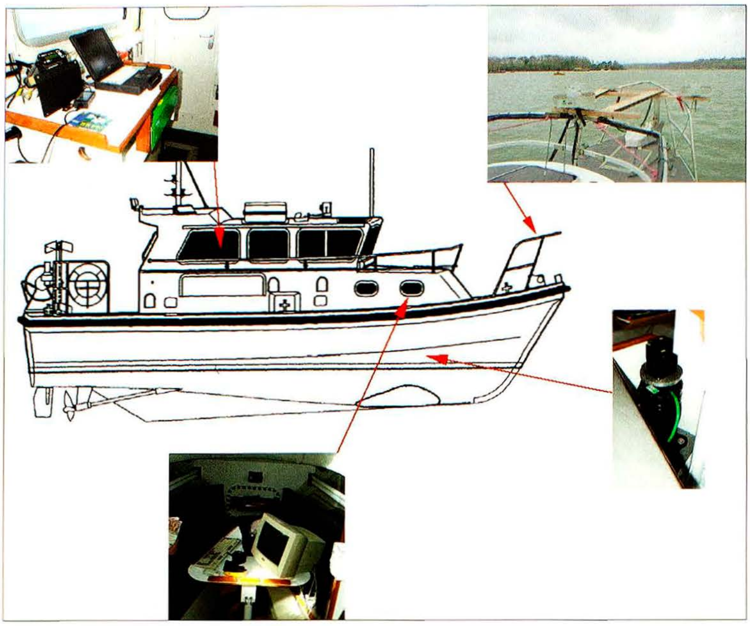

Figure 2: Marine trial configuration. Clockwise from top right a) POS/MV data collection PC, b) Ashtech GPS antennas, c) Crossbow IMU, d) Crossbow IMU data collection PC

installed so that a separate attitude solution from the GPS receivers could be computed if required for future trials. Two tests are described in this article where firstly, only one of the antennas is used, and secondly, two antennas are used in order to also derive a heading estimate. The antennas were located on the front of the vessel as it was the area that provided the easiest access, and experienced the least obstructions from the masts on top of the vessel. The GPS data was processed using differential carrier phase measurements over a short baseline of approximately 2-3km. The reference station was located on the roof of the Hydrographic School. A desktop PC was used to collect the data from the IMU, and all measurements were processed using KinPos[i].

An important consideration that had to be addressed when installing the GPS/INS system was the measurement of the lever arm between the IMU sensor and GPS antennas. The lever arm separation is the physical separation between the origin of the IMU sensor axes and the phase centre of the GPS antenna where the GPS signal is received. This separation is required to transform the position and velocity measured by the GPS receiver, to the position and velocity experienced by the IMU. The measurement of the lever arm separation is a challenging task, especially in a marine environment. This is not only because there is not direct line-of-sight between the IMU and the GPS antenna, but also because the marine vessel is typically moving around on the surface of the water.

The lever-arm separation between the Crossbow IMU, the GPS antennas and the POS/MV system was measured using a total station. Because it was not possible to measure the lever arm separations in a dry dock environment, the measurements had to be taken with the vessel resting on the water. The total station was positioned on the vessel itself in order to collect the measurements. This was so that any movement of the boat would also be experienced by the total station. The prism for the total station was located above each of the sensors and also on two further points that were used to compute the centre line of the boat. The prism was attached to a survey pole to measure the reference point for the IMU which was mounted beneath the hatch over the front cabin. The two reference points that were used to compute the centre line of the boat were used to rotate the measurements from the total station to the vessel reference frame. The coordinates were then translated so that the IMU formed the origin of the coordinate system. The separation between the GPS antennas was also measured using a steel tape measure to give a coarse check on the quality of the coordinates. In all cases, the maximum difference between the total station and tape-measured distances was 3mm.

Trajectory Description

The vessel trajectory for the marine trial is shown in Figure 3. The trajectory of the trial is very important for the analysis of the results because of the type of dynamic manoeuvres that were experienced. Figure 3 shows that there is an initial alignment section of the trajectory. During this period, the vessel performed a series of figure of eight manoeuvres which were performed to introduce horizontal accelerations to improve the estimation of the heading error and the initial bias errors. The alignment manoeuvres were performed for approximately 10 minutes. After the alignment section of the trajectory, the vessel then performed a series of survey lines up and down the course of the River Tamar with the survey lines increasing in length towards the end of the dataset. The survey lines lasted from 2 minutes to 8 minutes. The longer periods of straight lines were used to help assess the performance of the sensor during periods of low horizontal acceleration.

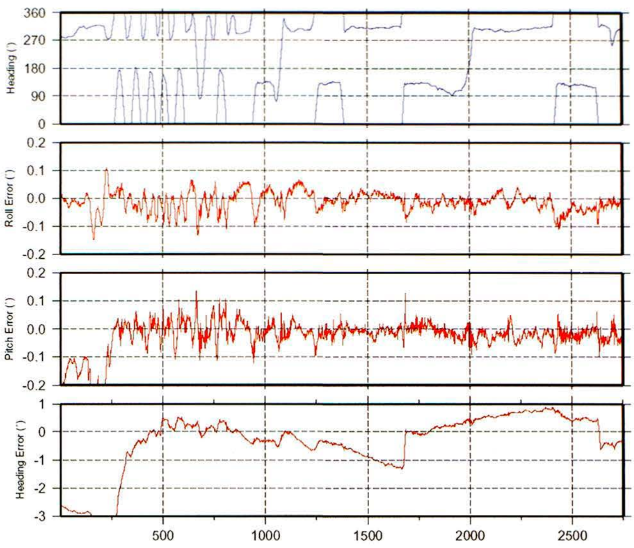

Figure 4: GPS and low cost INS attitude errors

Single Antenna GPS and Low Cost INS Results

Figure 4 shows the attitude errors using the low cost INS integrated with a single roving GPS antenna for the Plymouth trial. The trial can be coarsely divided into two sections: an alignment period between 250 and 900 seconds, and a navigation or surveying period after this time. The alignment period occurs at the beginning of the processing run, and is used to reduce the initial attitude errors. To obtain the initial heading, the heading has to be obtained from either an external aiding source such as a compass, or it is computed using the change in position of the vessel. The initial heading for the trial was initialised with an error of approximately 2.5 degrees. The roll and pitch were assumed to be zero due to the boat resting on the water. In the figure, it is clear that the alignment manoeuvre begins at 250 seconds, because the heading error is reduced by the Kalman filter and the bias in the pitch error is also removed. The alignment manoeuvres continue until 900 seconds when the survey lines begin. During the navigation part of the trajectory, it is shown that the roll and pitch errors are relatively constant. The heading error, on the other hand, drifts by up to 1.2° in some places. This is due to the low horizontal accelerations experienced by the vessel. When the vessel changes direction, the resultant position and velocity errors can be used by the Kalman filter to reduce the heading error.

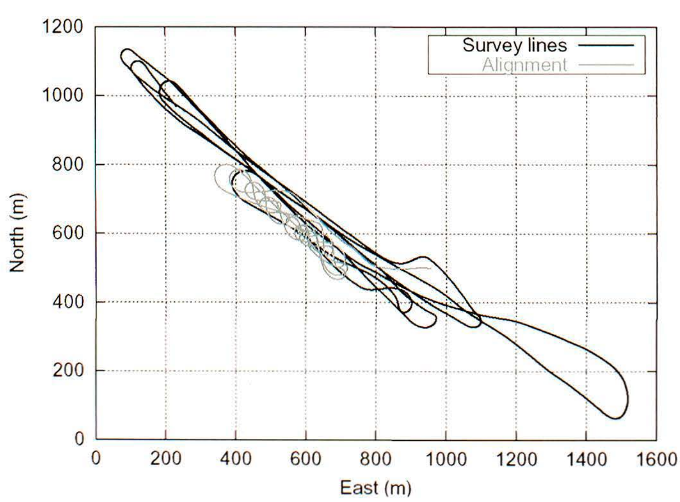

Figure 3: Marine trial trajectory

The attitude misalignments for the marine trial are summarised in Table 3. The table shows the standard deviation of the attitude errors, and the

		Roll	Pitch	Heading
Alignment	Standard deviation (°)	0.043	0.051	0.161
	Mean (°)	-0.033	-0.785	1.719
Whole dataset	Standard deviation (°)	0.034	0.041	0.522
	Mean (°)	-0.034	-0.774	1.667

Table 3: Attitude errors

mean error. The mean error was assumed to be due to the misalignment between the POS/MV IMU and the Crossbow IMU. The errors shown in Figure 4 have been compensated for this offset. The assumption that the mean error is caused by the misalignment between the sensors can only be validated by performing multiple trials in different conditions. Unfortunately, the vessel was only available to collect one dataset. It is possible that biases in the attitude errors may remain due to factors such as unresolved bias, scale factor and sensor axis misalignments. Therefore, the results from the marine trial have to be considered with this in mind.

Table 3 shows that during the alignment phase, the standard deviation of the heading error is only 0.16°, compared to 0.52° for during the navigation section. It is clear from Figure 4 that this is caused by the drift of the heading error during the periods of low horizontal acceleration. When the vessel performs a turning manoeuvre, the heading becomes realigned. This is obviously a significant problem for marine applications where long periods are experienced without the need for the vessel to manoeuvre. If the survey lines were to last longer than the maximum 8 minutes encountered here (which, of course, is very likely), it is expected that the heading error would be larger.

Another method for assessing the performance of the INS during the trial is to look at what is called the Kalman filter innovation sequence. The innovation sequence is the difference between the predicted INS and the estimated GPS position and velocity at each Kalman filter update. Figure 5 shows the innovation sequence for the marine trial for the north and east axis positions. The noise in the innovation sequence is a combination of the error in the GPS and the INS. The GPS was processed using the carrier phase data so the error in the innovation sequence from the GPS should be approximately 1-2cm. The figure shows that at the beginning of the dataset, the INS does not give a good prediction of the next position provided by the GPS. The difference is over 10cm in some places. However, as the INS becomes aligned, the INS and GPS positions match more closely. After the alignment manoeuvre, the standard deviation of the north and east axes position differences are 3.1cm and 3.2cm respectively. It is shown in the figure that there are some 'spikes' in the innovation sequences. These occur during the turning manoeuvres and are expected to be due to a combination of the IMU errors such as bias and scale factor errors, and the INS heading

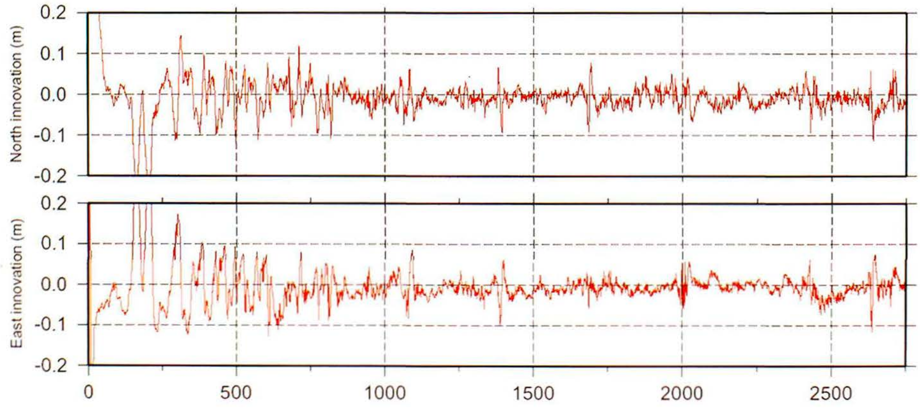

Figure 5: Kalman filter position innovation sequence

error. It was expected that the position differences would be smaller than 3cm, this is because the noise contribution to the innovation sequence from the GPS positions should be approximately 1-2cm. Factors that contribute to the INS errors are considered later in this paper.

GPS Gap Bridging

Another advantage of using a GPS and INS integrated system is the ability for the INS to bridge periods when the GPS is unavailable due to obstructions. To test the performance of the INS during outages, some gaps in the GPS data were simulated. The advantage of simulating gaps in the GPS data is that the GPS positions during the simulated outage can be used as a reference for comparison with the INS only solution. This gives an indication of the performance that can be expected if a true GPS outage were to occur.

Table 4 shows the maximum position errors averaged from 10 simulated GPS outages of 15, 30 and 60 seconds under different dynamic conditions. Two dynamic conditions are highlighted in the table to investigate if there is a difference in performance when the vessel follows an approximately straight trajectory, and when the vessel undergoes a turning manoeuvre. The table shows that the averaged maximum position errors obtained during 15, 30 and 60 second gaps are 0.88m, 3.38m and 16.50m. The maximum position errors from any of the 10 simulated outages were 1.53m, 5.11m and 24.12m. Also, the maximum velocity error for the outages was 0.6m/s. The table shows that there is no significant difference between the position errors in different dynamic conditions. It is shown that during short outages, the INS is able to provide position to better than 1m which is still useful for many applications. The table shows that from 15 seconds, the position errors increase to over 3 metres after 30 seconds and approximately 15 metres after 60 seconds. Although the position accuracies do not meet those required for applications such as marine survey, the INS may be useful to maintain navigation during short position outages. In addition, during these periods there was no significant degradation in the attitude accuracy.

	Maximum position error		
	15s	30s	60s
Low dynamics	0.88	3.38	13.99
High dynamics	0.74	3.08	16.50

Table 4: Standalone INS performance during GPS outages

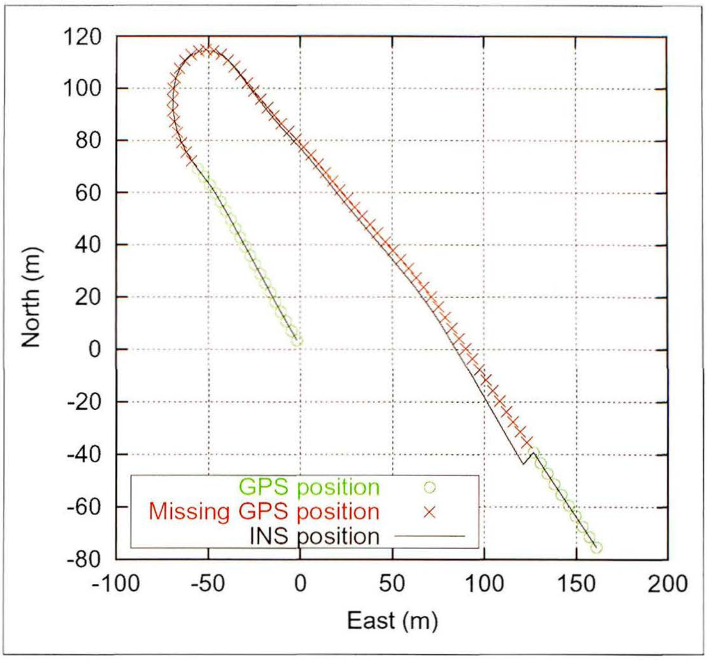

Figure 6: Standalone INS performance during 60 second GPS outage

An example of the drift during a GPS outage is shown in Figure 6. The coordinates are given in metres in the north and east directions to give a clear indication of the magnitude of the errors. The circles indicate that GPS updates that are available and the crosses indicate the carrier phase position (truth) during the GPS outage. The figure shows that the vessel travels approximately 300m during the 60 second outage. After 60 seconds, the position error is 11.05m which is approximately 4% of the total distance travelled.

Potential Error Sources

The results from the marine trial have shown that the low cost INS integrated with a single roving GPS antenna is not able to meet a typical requirement of 0.05° for applications such as marine surveying. There are many error sources that need to be considered if better performance is to be obtained from the same low cost sensors. Firstly, during the trial Doppler data was not available. This was due to the firmware upgrade to the receiver. Instead the Doppler data was obtained by differencing the raw GPS carrier phase measurements. A first order Taylor approximation was used to achieve this which typically results in lower accuracy velocity information to be used in the Kalman filter (Bruton, 2000). Further errors may have been introduced from the installation of the sensors in the marine vessel, in particular the measurement of the lever arm separation, and the misalignment between the Crossbow IMU and the vessel frame of reference. In order for the lever arm separation to be measured accurately, it is assumed that the IMU is mounted without any errors to the vessel frame. In fact, the results did show offsets between the Crossbow solution compared to the POS/MV solution. This also affects the accuracy of the measured lever arm separation. This could be improved with repeated trials in order to validate the results.

	Roll	Pitch	Heading
RMS error (°)	0.17	0.30	0.16
Integrated system error (°)	0.04	0.04	0.09

Table 5: GPS-only attitude errors

Other errors experienced were with the synchronisation of the IMU measurements. This was not achieved using one of the high accuracy time-tagging methods that have been developed at the University of Nottingham. Instead the time-stamping accuracy was expected to be accurate to approximately 6ms. In the future it is recommended that manufacturers of low cost COTS IMUs incorporate some form electronics to allow easier integration of the measurements with GPS.

It is thought that the most significant IMU error source is the bias variation in the sensor. The sensor measurements were corrected for temperature dependent variation using previously collected data. However, the repeatability of the temperature dependent bias may not be consistent. The bias estimates obtained still showed some temporal variation for both the gyros and accelerometers. All of these error sources are thought to be responsible for the increased errors that are obtained using the real data. The most significant error that results from the marine trial is the heading error. One possible method to reduce the heading error is considered in the following section.

GPS Attitude Estimation

In view of the results obtained from the low cost INS and single GPS antenna system, the data was reprocessed to include attitude measurements using multiple GPS antennas. When the data was processed, no specific GPS processing software was available for processing the GPS attitude measurements. Consequently the attitude measurements were obtained directly from the GPS carrier phase positions using simple equations. The heading was computed from position differences between two GPS antennas in the north and east axes. Roll and pitch measurements were also derived using the difference in height between the antennas.

Table 5 shows the attitude errors computed using the positions from the multiple GPS antennas. It is clear that the roll and pitch errors are significantly larger than those obtained from the single antenna and low cost INS system. This is because the height estimate from the GPS measurements is of lower accuracy than the horizontal position estimation. However, the heading error of 0.16° is an improvement over the one GPS antenna system. In view of the accuracies obtained from the GPS attitude solution, it was decided to include the heading estimate into the integration Kalman filter to reduce the problem of heading drift. The roll and pitch estimates were not used so that only two GPS antennas are required, reducing system cost.
Table 5 also shows the integrated system error when the GPS attitude estimates were used as observations in the integration Kalman filter. The table shows that the attitude accuracies approach the accuracies required for marine surveying applications. However, the accuracy still falls just outside of the 0.05° multibeam requirement from Trethewey (1999).

Figure 7 shows the heading error obtained from using only GPS measurements, and the integrated dual antenna GPS and low cost INS solution. The figure shows that the INS smooths the GPS heading estimate. The errors in the GPS heading are thought be due to multipath since atmospheric errors in the GPS measurements should affect all the antennas equally. The GPS heading accuracy can potentially be improved using a longer baseline, new GPS receivers with better multipath mitigation and more rigorous

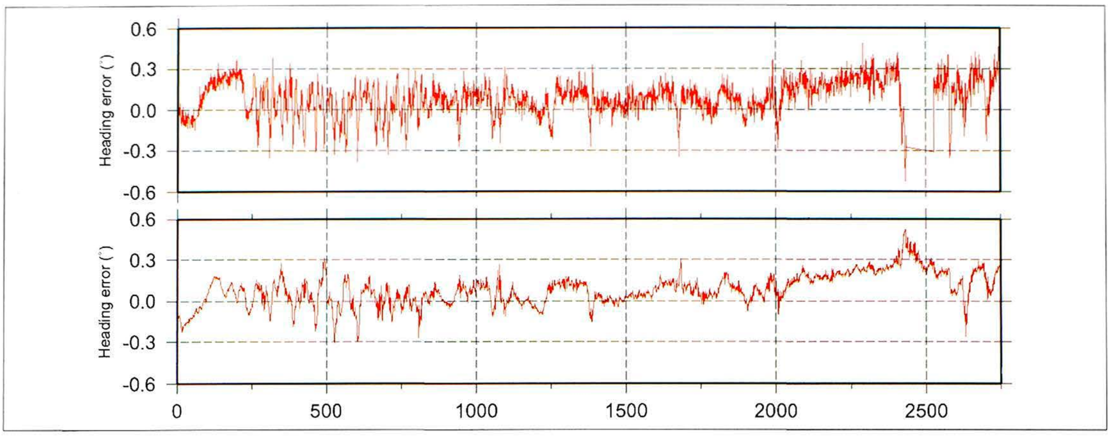

Figure 7: Integrated system heading error using GPS heading aiding

estimation of the attitude parameters using least squares or a Kalman filter (Lu, 1995). It is also shown towards the end of the GPS heading error time series, there is a short period where the GPS is unavailable. This is because loss of the ambiguities was experienced at one of the GPS antennas. The INS is used to give a solution during this period which again gives a more robust system. The INS could then be used to reacquire the integer ambiguities.

Conclusions

This paper has presented the design, implementation and results obtained from a low cost INS integrated with GPS in a marine environment. The system was put together using COTS components: the GPS receivers used were Ashtech Z-XII's; the IMU was a Crossbow AHRS-HDX-DMU 400CA; the data was collected using a desktop PC; the data can be synchronised using an ADAC PCMCIA A-D converter; and the data was collected and processed using software from the University of Nottingham. The results obtained from the system demonstrate that the low cost INS is capable of achieving attitude accuracy that approaches the accuracy required for geo-referencing a multibeam sonar in a marine environment. Integrating the Crossbow IMU with a single roving GPS antenna, the roll and pitch accuracy's were less than 0.05°, but the heading error was 0.51°. In addition, the accuracy of the heading could degrade further depending on the vessel dynamics. Using two GPS antennas integrated with the low cost IMU resulted in roll and pitch accuracy's of less than 0.05°, and heading accuracy of less than 0.1°.

Further advantages were also shown in using the INS in that the system provides improved accuracy and reliability over, for example, a system that uses solely uses multiple GPS antennas to derive attitude. For example, during a 15 second GPS outage, the INS was able to provide positions to better than 1 metre accuracy. Also during the outage, the attitude errors did not deteriorate. The cost of the GPS and low cost IMU is greatly reduced over a traditional GPS and tactical grade IMU system. This is because the tactical grade IMU forms the most significant part of the hardware costs in the system. An equivalent low cost IMU to that used in the trial can now be purchased for approximately one quarter of the price of a tactical grade IMU. The higher cost system still requires a second roving GPS antenna in order to stop the INS heading from drifting over time, therefore the cost of the GPS hardware will be the same. Potential improvements can be obtained in future trials, for example, through providing more precise synchronisation of the sensors, and more accurate measurements for the initial installation. The cost of inertial components is constantly decreasing, and the performance is improving. Such a low cost system is expected to fully meet the stringent attitude accuracy requirement for marine surveying in the near future.

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References

Barbour, N.M., (2003), Inertial Navigation Sensors, *NATO Research and Technology Organisation lecture series 232 Advances in Navigation Sensors and Integration Technology, London*, UK, 20-21 October 2003

Bruton, A. M., (2000), *Improving the accuracy and resolution of SINS/DGPS airborne gravimetry.* Ph.D. thesis, University of Calgary

Green, J.A., (2004), Progress in Integrated Gyroscopes. In: *Proceedings of the IEEE Position, Location and Navigation Symposium, Monterey, California*, 26-29 April 2004

Hanse, J.G., (2004), Honeywell MEMS inertial technology & product status. In: *Proceedings of the IEEE Position, Location and Navigation Symposium, Monterey, California*, 26-29 April 2004

Hide, C.D., (2003). *Integration of GPS and low cost INS measurements, PhD Thesis*, University of Nottingham

Scherzinger, B.M., (2000). Precise robust positioning with Inertial/GPS RTK, in Proceedings of ION GPS 2000, In: *The proceedings of the 13th Technical Meeting of the Satellite Division of the Institute of Navigation, Salt Lake City, Utah*, 2000

Schmidt, G.T., (2003). INS/GPS technology trends, *NATO Research and Technology Organisation lecture series 232 Advances in Navigation Sensors and Integration Technology*, London, UK, 20-21 October 2003

Trethewey, M., Field, M., Cooper, D., (1999). Making the most of investment in multibeam sonar. *International Conference on Shallow Water Survey Technologies, The Defence Science and Technology Organisation*, Sydney Australia

TSS (UK) Ltd, (1999). *POS/MV Model 320 Ver 3, Position and Orientation System for Marine Vessels System Manual*

Wolf, R., Eissfeller, B., Hein, G. W., (1997). A Kalman filter for the integration of a low cost INS and an attitude GPS. In: *Proceedings of the International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation (KIS)*, Banff, Canada

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