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SENSORS II SESSION

Acoustically Aided Inertial Navigation - Proven, Robust, and Efficient, Positioning Solutions

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Abstract

Introduction

History of Inertial Navigation Systems

Inertial navigation is based on the principals of dead reckoning. By knowing your start location and subsequent speed and direction you can work out where you will be at some time in the future. Of course, the accuracy of dead reckoning navigation is related to the accuracy of the information you have about your movements. Errors in dead reckoning navigation accumulate over time, and to make safe use of this form of navigation it is essential to understand how these errors grow and make subsequent decisions based on knowledge of that error.

Before the invention of accurate chronometers by John Harrison in the 1760's all longitude calculations were based on dead reckoning, including the discovery of America.In 1906 the first practical marine gyrocompass was patented in Germany by Herman Anschultz-Kaempfe, Elmer Sperry filed his own patent in America in 1908. Marine gyrocompasses were used extensively throughout the First World War, but it was during the Second World War and the German V2 rocket that brought together two gyroscopes and lateral accelerometers with an analogue computer to form the first recognisable inertial navigation system. The team who developed the V2 guidance system during WW2 led by Von Braun surrendered at the end of the war and moved under Operation Paper clip to the US where they continued their work on inertial navigation. Building on the German technology, the USA introduced the Atlas ICBM's in the 1950's using inertial navigation. In 1958 the USS Nautilus transited under ice to the North Pole navigating primarily on INS. In the 1960s the Apollo program travelled to the moon and back using INS.

The first major civilian use of inertial navigation was with the Boeing 747. Right from the introduction of the aircraft in 1969 747s were equipped with multiple inertial navigation units.

In the 1980s practical ring laser gyroscopes were introduced. Ring laser gyroscopes were a big improvement on previous mechanical systems, reducing power consumption as well as weight and physical size.

The Ring Laser Gyroscope

The ring laser gyroscope (RLG) is typically a triangular shaped laser cavity (usually helium neon) with a single cathode and two anodes. At each apex of the triangle is a mirror. High voltage between the anode and cathodes provides enough energy to cause regenerative lasing action within the cavity (1). The shape of the cavity and the dual anodes causes two counter propagating beams to be generated within the cavity. The speed of light is constant, but as the laser cavity rotates one beam will have to travel further than the other beam to complete a full circuit of the cavity. This is known as the Sagnac (2) effect and is the principal behind all optical based gyro compasses. The frequency of the laser been is determined by the path length around the cavity, so if one bean has further to travel than the other, there will be a difference in the frequency of each beam. This frequency difference is proportional to the rotation rate and is the parameter that is measured in an RLG.

The main drawback of RLG technology is due to the fact that the mirrors can never be perfect. There will always be a proportion of each wave that is reflected back from the mirrors (backscatter) When the frequency of the beams is close, i.e. at very low rotation rates, the backscatter energy causes the frequency of the two beams to lock together (1). To overcome this RLG "lock in", a dither motor is added to the system to vibrate the whole assembly back and forth at a suitable high frequency (usually around 400Hz).

The dither motor means that the RLG is no longer a solid state device, it contains mechanical components that are subject to wear and require periodic maintenance. The high voltage discharge electrodes also wear with time, and maintaining the device entirely gas tight can be problematic.

The Fibre Optic Gyroscope

The fibre optic gyroscope (FOG) is based on the same Sagnac effect as the RLG, however in the FOG the light source is external to the gyroscope and there is no potential for lock-in. FOG's were made possible by the development of high grade optical fibre and components by the telecommunications industry in the

1970s but initially FOGs were limited to only medium grade gyroscopes (1 to 10°/hr). Steady advances in the field of Fibre Optic Gyroscopes have now lead to units that are capable of the most stringent requirements, operating at levels better than 0.001°/hr. (3)

An FOG operates by using a solid state laser gyro to generate the initial light beam. This beam is split in an optical component and sent around a long coil of optical fibre in two opposite directions. As with the RLG, if the FOG rotates while the light beams are propagating, one beam will have further to go before it exits the coil than will the other. This difference in the path length caused by the rotation of the FOG is detected as a phase difference between the two exiting light beams. Because the fibre coil is entirely passive, there is no potential for the energy from the two beams to mix therefore lock-in is not a problem for the FOG.

FOG technology is entirely solid state, using passive optical fibre, diode based lasers, and, integrated optical components for beam splitting and phase detection. Operational lifetime of an FOG can be extremely long, and is typically limited by the lifetime of the solid state electronics making up other parts of the system.

The Modern Inertial Navigation System.

As mentioned previously, an inertial navigation system calculates positions based on an initial starting position and subsequent movements. A modern INS typically integrates data from three accelerometers and three gyroscopes arranged in an orthogonal triad. Intuitively we assume that the major error component within an inertial navigation system would come from the accelerometer measurements, after all, acceleration is integrated to get speed and a speed error obviously leads to a position error. However we need to remember that we are navigating on the surface of a rotating sphere. Errors on the measurement of rotation (in the direction of Earth rotation) will cause an error of position. (4)

INS Drift in Nm/h = 60 x Gyro Bias in deg/h

Hence, 0.01 deg/h gyroscopes lead to an inertial navigation system that will have a free inertial drift rate of 0.6Nm/h. The vast majority of commercial inertial navigation systems fall in to this class of instrument. The major market for these systems has been aircraft where this level of free inertial drift is manageable, but for the longer duration voyages encountered at sea we need to improve on the free inertial drift rate of these sensors.

A modern inertial navigation system will measure rotation rate and acceleration many hundreds of times per second. Rotation and Acceleration may be integrated to give heading and velocity data, this is further integrated to give position data. Typically systems will use a Kalman filter to combine internal measurements with externally applied aiding data. The Kalman filter estimates the errors in the system and these errors are fed back in to the calculation to produce a better position estimate. It should be noted that errors are multiplied at each stage of integration; Corrections at the level of rotation rate and acceleration have more effect in the overall solution that corrections at the velocity and direction level. Likewise, corrections at the speed and direction level have far more effect of the results than corrections at the position level.

Another aspect of the modern inertial navigation system that should be considered is the input rejection filter. Each type of aiding input has an error model associated with it. Incoming data is compared to the state of the internal navigation algorithm and with the input error model. If the incoming data is not consistent with the error model and how it relates to the internal Kalman state then it is assumed to be false and hence is rejected. It is important to keep inconsistent data out of the Kalman filter, as erroneous data will corrupt the error estimation and will therefore degrade future position calculations.

Any system of gyroscopes capable of measuring rotation accurately enough for an inertial solution will as a side effect be capable of providing vessel heading and attitude to a very high accuracy. Gyroscope accuracy is always a function of latitude, the higher the latitude, the worse the accuracy of the Gyroscope. Gyro accuracy is expressed as a function of the Secant of the working Latitude. i.e. a standard navigation gyroscope is specified around 0.3deg seclat while a high grade FOG base gyroscope would be around 0.1deg sec lat, and an inertial navigation system needs to be around 0.01deg seclat. When we plot the resultant accuracy against latitude we can see that as we approach the pole, using a standard navigation gyroscope becomes impossible, but inertial navigation systems will remain useful even at very high latitudes. Effectively as a side effect of using inertial navigation we extend our capability to operate at very high latitudes.

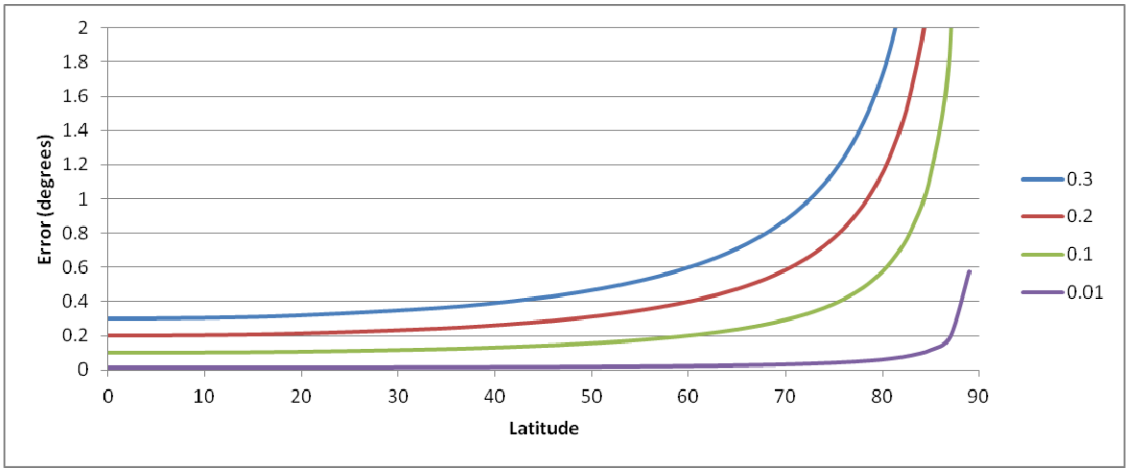

Figure 1 Gyroscope accuracy with Latitude

Inertial Navigation Aiding

GPS

Over the long term, GPS is very accurate, however over the short term a certain amount of positioning noise is typical. The characteristics of short term noise and long term accuracy are generally complementary to the INS characteristics of very smooth positioning in the short term with long term accuracy being poor. INS has been very successfully combined with GPS in the land and hydrographic market, particularly where GPS signals may be temporarily disturbed by navigating close to obstructions such as buildings or bridges. The relatively short nature of these disturbances means that the INS has little chance to drift before correct GPS data is restored.

In the dynamic positioning environment of today, we have to deal not only with very short term perturbation of GPS, but also with relatively long ones. A DP vessel may be required to hold station close to a large structure for days at a time. In the worst case scenario, multipath can affect data from multiple satellites at the same time causing the GPS position to "drift" before failing entirely. The same kind of effects can be caused by atmospheric scintillation.

An INS has no method to detect the difference between a position aiding sensor that is drifting and its own inertial drift. So long as the GPS position drifts in a smooth manner, the INS will continue to assess its own internal errors based on the aiding data received and will interpret the disassociation between the aiding data and its internal state as an error of its internal sensors. In effect the INS will follow the drifting GPS until the GPS signal fails altogether or jumps back to the correct location. When GPS does return the INS will take some time to recognise it as correct. The input filter will initially reject the GPS data because the error model does not allow a large inconsistency between INS position and GPS. Only after a period of time where the internal INS error state has grown sufficiently large will the GPS data be accepted in to the calculation once more.

Acoustics

Acoustic positioning systems are not generally considered to be subject to drift. Other than a system failure, the only environmental impact that could cause drift in an acoustic positioning system is water column sound velocity profile changes. Changes in water column velocity characteristics are easily measured, but more importantly, can be completely mitigated with a correctly designed array of reference beacons. In general Acoustic positioning systems can be considered drift free but noisy.

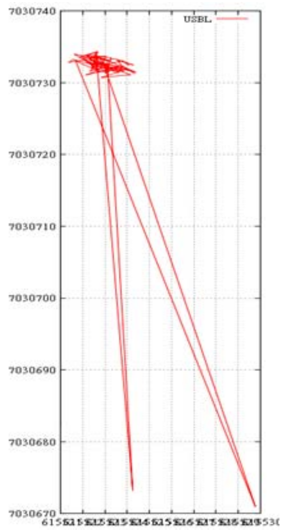

Figure 2

Figure 3

Figure 2 shows typical USBL data from a well calibrated system. Throughout this paper, we will look at a data set from a USBL positioned ROV equipped with INS and DVL. The data section analyzed covers a time period where the ROV was static on the seabed at a water depth of 850m (2788ft). The data set is exactly analogous to USBL data from a vessel holding station and using a fixed seabed beacon as a reference.

Figure 3 is a close up of the main cluster of positions output by the USBL system with the two obvious positioning spikes removed. The CEP_{95} is indicated with the solid red line.

The USBL data has a CEP_{95} of 1.87m, which is pretty good performance for USBL in this water depth. However we shall show how with the addition of other sensors a much higher accuracy is achievable.

As mentioned previously, the ROV which was sitting on the seabed and hence static, equipped with an inertial navigation system (IXBLUE PHINS). If we re-process the Inertial navigation data, using only the USBL to aid the inertial navigation system we get the results shown in figure 4.

Now the CEP_{95} is 0.48, This is a 389% improvement over stand alone acoustics, and is already better than DGPS, and is approaching the capability of high accuracy GPS services. We clearly see from the data that the two large spikes the original USBL data set have not impacted the inertial calculation, in fact these two spikes have been entirely excluded from the calculation by input rejection filter. The INS produces a much higher update rate than is possible with acoustics alone, and produces a much smoother position.

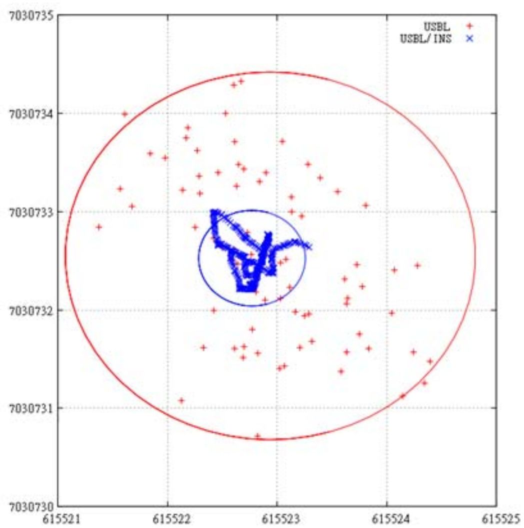

Figure 4

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The accuracy improvement by adding an INS to an acoustic positioning system is clear, and if the aim is simply to produce GPS like positioning while on acoustics then we need do no more, however we have not yet greatly improved the robustness of positioning. Without the Acoustic input, the INS would quickly drift, at a rate around 0.6Nm/h. In effect by using an INS aided acoustic system we have increased system complexity, improved precision, but done little to increase robustness.

INS aided acoustics

- Precision improved to be better than DGPS.
- Update rate improved to be better than DGPS.
- System Complexity increased.
- Robust to short acoustic dropouts.
- Not robust to acoustic system failure.

INS Velocity Aiding

Doppler Velocity Logs (DVLs) are able to measure the speed of travel over the sea bottom to an accuracy of a few mm/s. (4) Using this velocity information to aid an INS is far more effective than providing position based aiding data. The velocity data is integrated in to the positioning algorithm at the mid stage, whereas position information can only effect the calculation at the final stage. DVL systems are now available that can operate in well over 1000m of water, making them potential aiding sensor for surface navigation.

The characteristics of an INS aided with DVL are particularly interesting in the DP market. The DVL changes the drift specification from one that is primarily based on time, to one that is based on distance travelled. For example, the iXBlue PHINS which has a free inertial drift rate of 0.6Nm/h, when coupled with a DVL has a drift rate specified as 0.1% of distance travelled (6ft in a Nmi).

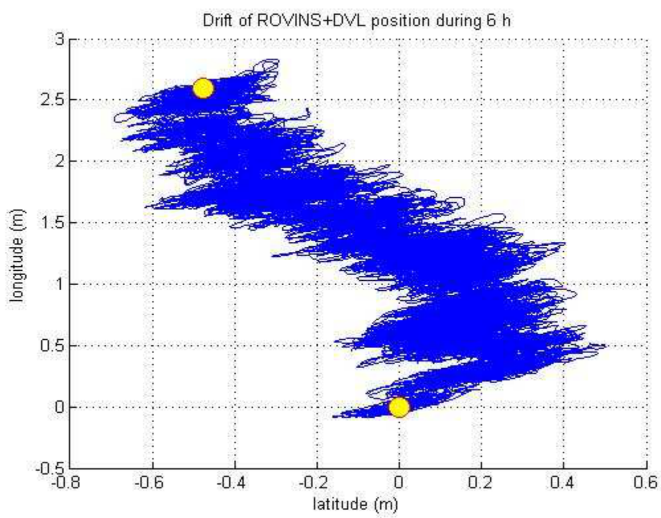

Figure 5

To generate figure 5, an Inertial Navigation System was close coupled to a Doppler velocity log and deployed over the side of a small vessel. The vessel was tied up alongside over night, and data from the INS was logged continuously. The vessel was not entirely static, and was moving slightly with the swell and tide. The plot shows how the INS position varies over a 6 hour period. Of course, this data is atypical for the DP market as the vessel is in very shallow water, the DVL quality is the absolute best, and the update rate is high.

It is natural to assume that a high DVL update rate will produce higher quality positioning; however, external aiding data is used to estimate the errors on the internal sensors. The internal sensor errors do not change quickly, therefore even extremely widely spaced DVL updates are able to stabilize the inertial drift. Experimentation on a 1.7km long pipeline survey showed that even very slow update rates are capable of effectively correcting the INS drift

DVL Update Rate	**Error, % distance travelled.**	**Drift speed m/h**
1s	0.03%	0.18
2s	0.13%	0.82
3s	0.26%	1.67
4s	0.27%	1.77
6s	0.32%	2.08
8s	0.30%	1.98

Returning to our example data set, we have re-processed the inertial data, this time applying DVL data with an update rate of only once every 3 seconds in order to simulate the data that would be available in a DP Situation.

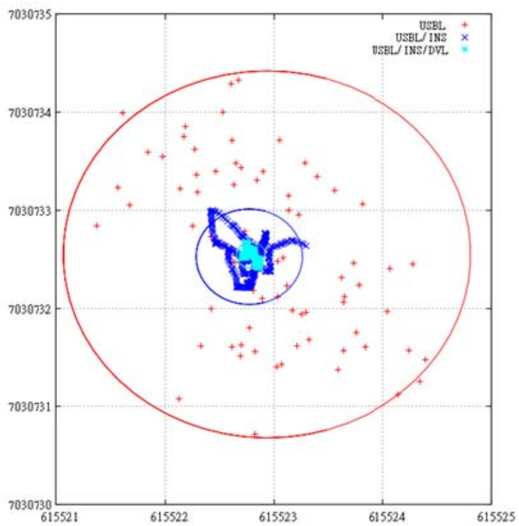

Figure 6

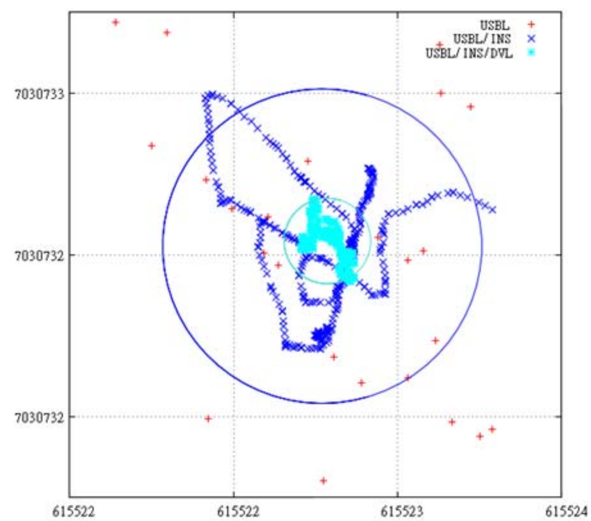

Figure 7

Figures 6 and 7 show the INS data, now aided with USBL and DVL. The CEP_{95} is now 0.13m, certainly as good as the best offshore DGPS (Float RTK).

In order to consider the system as we have it now as a major improvement over GNSS based systems, we need to prove the performance of the system when the acoustic system fails for a significant length of time. To do this we can re-process the data once again, this time we exclude the USBL data to produce a plot that uses only INS and DVL data.

The perhaps surprising result shown in figure 8 is that rather than being degraded by the loss of the USBL aiding data, the positioning is improved. CEP_{95} is now 0.076m, some 23 times (2300%) better than the

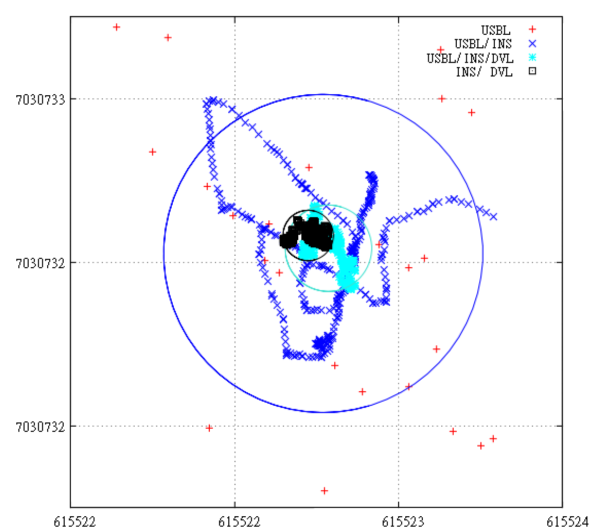

Figure 8

USBL alone. Of course if we had significantly more data to analyse we would see that eventually the INS DVL data would drift.

Figure 9 shows data from a trial conducted in early 2010. A PHINS DVL and 300kHz RDI workhorse were mounted on a DP survey vessel. The vessel was holding station using GPS in 80m of water. The PHINS was mounted on the deck some distance from the moon pool. The DVL was deployed on a pole through the moon pool meaning that the coupling between the DVL and the INS was particularly poor. In this situation we find that the INS DVL drift rate is approximately 2.5m per hour. Also note that the data set includes the PHINS position SD as reported by the INS. At no point does the INS position quality estimate exceed reality, in fact, the INS is somewhat conservative in estimating it's own performance.

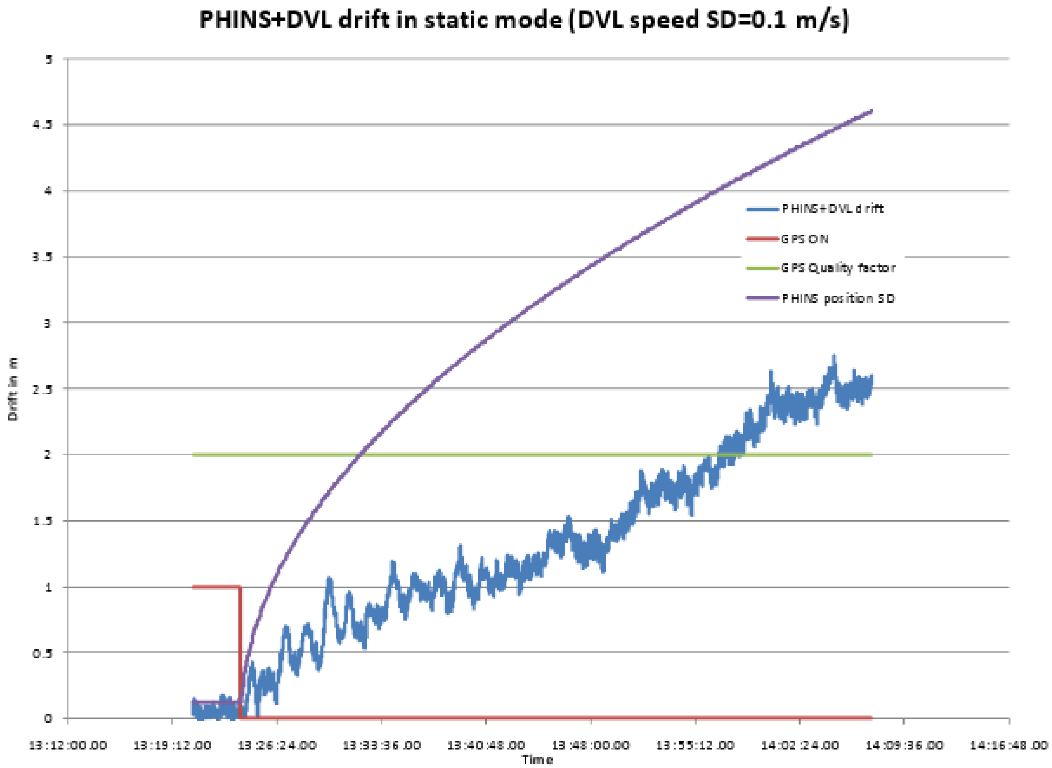

Figure 9

INS & DVL aided acoustics:

- Precision improved to be better than high accuracy DGPS.
- Update rate improved to be better than high accuracy DGPS.
- System Complexity increased.
- Robust to lengthy acoustic dropouts.
- Robust to acoustic system failure.
- Robust to DVL failure (accuracy drops back to INS & Acoustics level)

Other Aiding Sensors

This analysis has so far mostly covered USBL aiding of INS, and has discussed the unique effect of adding a DVL in to the solution. It should be noted however that general purpose inertial navigation systems are capable of receiving aiding data from many more types of systems than this. Another kind of data that may be accepted by an INS is range based data. In the acoustic domain this is generally referred to as LBL, though SBL can also be considered primarily a range based system. Higher in the frequency spectrum are radar and laser based ranging systems.

If we consider classic LBL systems, a minimum of three ranges are required for unambiguous positioning (figure 10).

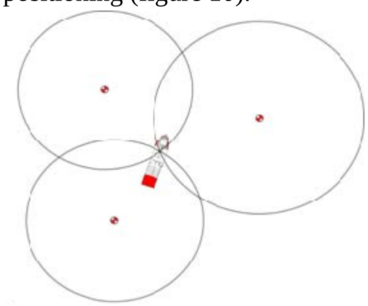

Figure 10

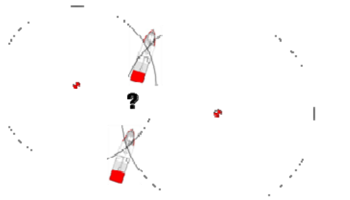

Figure 11

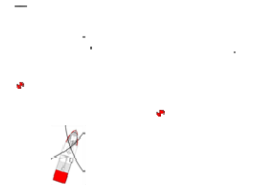

Figure 12

If we only have two ranges available, it is impossible to identify which of the two points where the ranges intersect are the valid location (figure 11). Of course, if we are using an inertial navigation system, and have previous knowledge of our location (figure 12), then the ranges from the two beacons will aid the INS, removing any chance of inertial drift, and therefore will keep the positioning solution locked on to the correct location.

In February 2012 Nautronix deployed a NASNET system in Loch Linnhe Scotland for testing purposes. Part of the testing was to confirm the implementation of interface protocols between iXBlue PHINS and the Nautronix NASNET system. This testing involved a PHINS unit installed on a barge moored at the center of the acoustic array. Messages where supplied to the INS consisting of the location of the beacon and the range to the beacon, various quality information, including an estimation of the accuracy. The barge was also equipped with DGPS for comparison purposes. The barge was anchored fore and aft along the length of the loch, the narrowness of the loch precludes side anchors and so the barge was able to swing a considerable distance across the loch. It was rather unfortunate that RTK positioning was not provided as subsequent processing of the recorded data would indicate that the INS was able to position the barge to a higher precision than was achieved by the GPS system.

Figure 13

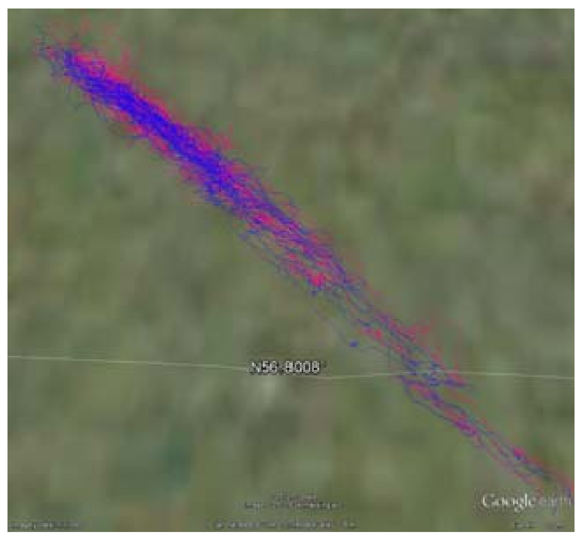

Figure 14

Figure 13 shows the location of the barge in relation to two of the NASNET beacons. Figure 14 shows both the GPS data (in red) and the INS data (blue). Because the barge is moving so much, it is hard to quantify the actual performance of either the GPS or the acoustically aided INS, but it is clear that the spread of positions from the INS is smaller than those from the GPS. It is hard to see how this data can be used to quantify the performance of the system, other than to confirm that the INS is performing as predicted in figure 12, and the ambiguity illustrated in figure 11 has been overcome.

Inertial navigation systems operate on a global scale, the rotation of the earth is an important factor in how they work. As such, they need to work with global coordinate systems and do not operate well with relative based aiding. In the DP environment this can be problematic. One approach is to use a GPS position to initialize the inertial navigation system, then when a relative positioning system is required, the position of the INS can be used along with Simultaneous Localization And Mapping (SLAM) techniques to provide an initial calibration of the relative position sensor(s) once the SLAM process is complete a transformation may be performed on the relative positioning system to provide data to the inertial Kalman filter in a global coordinate system. This process is at the heart of the newly launched iXBlue system PD-PHINS.

Further work is required in order to integrate additional aiding sensors such as Fanbeam, CyScan, Taut wire, Artemis, Radius, RadaScan, etc.

Conclusions

Inertial navigation systems have been in use for nearly 80 years, in civilian use for over 40 years, and in the last 10 years have become common place in all kinds of survey applications, whether it be on land, at sea, or in the air. They are becoming standard equipment on remotely operated vehicles and are essential for autonomous vehicles either in the air or under the water. INS represents a mature reliable technology with significant potential to solve problems in the DP environment.

Significant benefits can be achieved by adding an inertial navigation system to any acoustic positioning system, greatly improving the update rate and precision of these systems, but even more benefits are available if aiding the INS with additional sensors.

	CEP_{95}	Improvement over USBL
USBL	1.87m	-
USBL & INS	0.48m	3.9
USBL, DVL & INS	0.13m	14.4
INS & DVL	0.076m	24.6

Results of the analysis of the ROV data set discussed here are directly in line with expectations discussed by Stephens in Integration of an inertial navigation system and DP (5) Stephens discussed the reduction on thruster demand when using INS with GPS and showed a 28% reduction in expected fuel consumption as well as showing that the likely drift of a typical supply ship with no available PMEs would be more than the expected inertial drift over periods up to 300s.

The analysis here indicates that by combining aiding sensors to an inertial navigation system higher positioning quality and perhaps improved robustness is achieved. By introducing sensors that are not normally considered suitable for DP use the issue of inertial drift can be overcome even when none of the usual PMEs are available for significant periods of time.

DVL aided INS, while not entirely eliminating position drift, do reduce the drift rate to a level that is easily manually controlled. As a backup to existing PMEs DVL aided INS can give bridge crew essential time to move the vessel out of a dangerous situation without experiencing unexpected run-off.

Works Cited

1. **King, A. D.** Inertial Navigation - Fourty Years of Evolution. *GEC Review, Vol 13, No. 3.* 1998, pp. 140 - 148.

2. *The luminiferous aether demonstrated by the effect of the wind relative to the aether in a uniformly rotating interferometer.* **Sagnac, Georges.** 1913, Comptes rendus de l'Academie des Sciences Vol.95, pp. 708-710.

3. *Ultimate-performance fibre-optic gyroscope: a reality.* **Herve C. Lefevre.** Kaohsiung : s.n., 2011. OptoeElectronics and Communications Conference . pp. 75-78.
4. *From high technology to solutions: the experience of iXSea.* **Gaiffe, Thierry.** Boston : IEEE, 2006. IEEE Oceans.
5. *Integration of an Inertial Navigation System and DP.* **Richard Stephens.** Houston : Marine Technology Society, 2008. Dynamic Positioning Conference. pp. 3-11.