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Sensors II

Integration of an Inertial Navigation System and DP

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ABSTRACT

The paper describes an architecture for the integration of an inertial navigation system (INS) into a dynamic positioning (DP) system. It discusses the major benefits of using INS for DP, and includes the results of sea-trials conducted to show these benefits.

There are a number of possible benefits to using an INS as an input to the DP system. These benefits are dependent upon a range of factors including the operations being undertaken by the vessel, the ease of use and the quality of the equipment.

One use of an INS is to supplement or clean-up measurements from an existing measurement system. By coupling the INS to a hydro-acoustic system the INS can help to reduce the noise on the measurements and fill-in for long update rates, for example, to prolong battery life for transponders.

A further use is to act as an independent position measurement system in the event of outages. In this configuration the INS can provide position measurements during short outages (up to a few minutes) of all other PMEs.

In order to gain the greatest advantage, the integration of the INS with the DP system is key. A flexible architecture allows the INS to be used to its full potential. The architecture described allows INS-DP integration that is easy to install and maintain and also allows dynamic reconfiguration to make the most of the available PMEs or to provide the greatest advantage for a particular application.

The paper further describes sea-trials performed to assess the ability of an INS system to provide the advantages described above. They include full-scale trials of INS performance at sea with a number of GPS outages. Also, performance of INS with acoustics-only is assessed from real-life data on a trial vessel.

INTRODUCTION

The vendors, owners and operators of DP systems are continuously striving to improve the safety, availability and efficiency of their systems. One area particular interest is in the position measurement equipment or PMEs. The operation of a DP system is often critical: lives depend upon it. It is therefore imperative to have reliable measurements of position. For safety critical operations, physical redundancy of measurement systems is a legal requirement. Specifically, three independent measurement systems must be employed for Class III operation in which life is at risk: where “independent” means having no common mode of failure.

The measurement of heading is usually achieved using one or more gyrocompasses. These devices have a long history, are reliable and accurate. Physical redundancy with independence is achieved by simply adding more units.

Position measurement systems utilize the global positioning systems (GPS) (Parkinson and Spilker, 1995), acoustics, taut wires, optical methods and others (Faÿ, 1990). Independence between position measuring equipment (PME) is more difficult. For example, GPS systems are susceptible to disturbances in the ionosphere, so different GPS receivers cannot be considered to be independent.

The use of inertial navigation systems (INS) to provide an enhanced measurement system has been proposed (Vickery, 1999). Inertial navigation systems use measurements of acceleration to estimate the motion of a vessel in an inertial reference frame. However, due to physical processes associated with the acceleration due to gravity, plus inherent accuracy and noise within the device itself, a degree of drift on the position measurements will always be present (King, 1998). Hence there is a need for periodic updates to the INS estimates of drift. These updates can come from another position measurement system, for example, GPS or a hydro-acoustic system.

There are clear advantages with using an INS to supplement a hydro-acoustic positioning system (Paturel, 2004, Faugstadmo and Jacobsen, 2003). These include improving position accuracy in deep water, increasing battery life by allowing reduced 'ping' rates, and providing short-term fill-in for outages.

The claimed benefits of INS have not been tested in action, however. This paper presents some live testing using combinations of INS, GPS and ultra-short baseline (USBL) hydro-acoustics in an attempt to evaluate the potential gains.

The full potential of the INS system can only be realized with an approach to the architecture of the whole DP system. Proposed architectures are discussed in a later section.

INS AND ACOUSTICS

The problems of deep-water acoustics are well known (Stephens, 2004). The depth introduces long ping cycle times due to the distance for the sound to travel, unless so-called *ping stacking* is employed. Deep water also increases the cost of replacing batteries in transceivers, which starts to become a significant proportion of the overall cost of the system. By increasing ping cycle times the battery life can be extended. Ping stacking only serves to reduce the battery life. Unfortunately, the increased ping times can adversely affect the DP control. This is true even though it is straightforward to configure the DP Kalman filter controller to make use of long measurement update rates. It tends to lead to higher thrust usage as the DP system detects deviations later and has to apply greater adjustments in thrust. Any changes in environmental forces or small inconsistencies in the DP's vessel model are exacerbated by a long ping time. There is also the possibility that aliasing effects due to long position measurement periods will introduce increased noise into the position measurements.

With an integrated INS, the long ping times can be reduced by using the INS to fill-in between pings.

In order to investigate the benefits of this approach, a number of tests have been conducted on a two small vessels utilizing an IXSEA hydro-acoustic system, combined with a PHINS inertial sensor. The tests were performed in USBL mode in 15 m water depth off Brest, and in 1000 m water depth off La Ciotat, on the south coast of France. In the deeper water, the shortest ping cycle time, without ping stacking, was 3 s, therefore data was collected at that rate. Both raw acoustic data and PHINS corrected positions were logged. An additional signal was generated from the PHINS using acoustic measurements sampled every 21 s rather than 3 s.

While it was not possible to install a DP system on the vessel in the time-scale of the trials, the results have been post-processed using a simulation of the DP to estimate the behavior of a DP vessel under the same conditions. The measured errors from the INS trials have been imposed on the simulation and comparisons made between raw acoustic signals at 21 s updates and acoustics plus INS.

The following figures show some results of such a simulation. Figure 1 shows a comparison of the vessel position errors during the simulation runs. It shows that the position keeping is significantly improved by using the INS corrections. The standard deviation of X-axis errors for acoustics only is 6.8 m while using INS reduces this to 3.4 m.

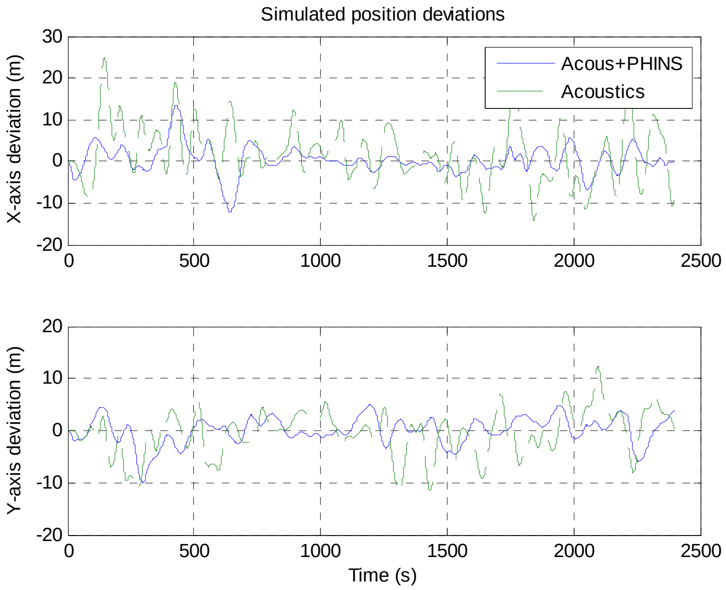

Figure 1 – position errors 21 s acoustics with/without INS in-fill

This provides a better balance between the respective weights of the INS+Acoustics and DGPS in the DP system, as the INS+Acoustics data is more accurate and comes at a higher recurrence than the pure acoustic data. This feature provides additional robustness to the full system.

An even greater improvement is achieved in the thrust demands from the DP system for the same scenario. Figure 2 compares the thrust demands with and without the INS corrections. It shows that thruster usage is dramatically reduced when the INS is filling-in between pings.

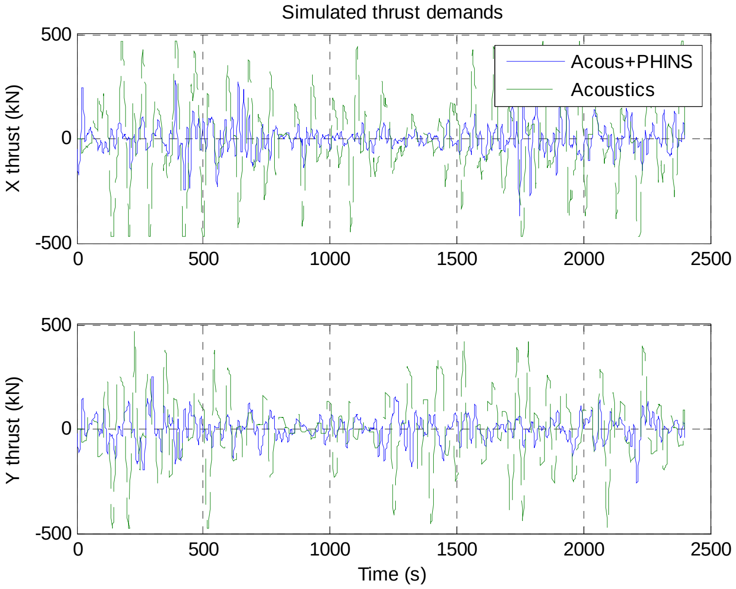

Figure 2 – thrust demands for 21 s acoustics with/without INS in-fill

This reduction in the thrust demand variation means less mechanical fatigue, less wear and reduced maintenance. Another consequence is a reduction of the thruster-generated noise in the water, which means better acoustic detection through an improved signal to noise ratio, not only providing more accurate and secure acoustic positioning, but also enabling operations in deeper waters.

A further illustration is gained by comparing the fuel consumption during DP. By estimating thruster power, P, from thrust, T, using the approximate relationship: $P \propto T^{1.5}$, the relative fuel consumption can be estimated (Lewis, 1988). Figure 3 shows the evolution of relative fuel consumption calculated in this way. It reveals that the INS can reduce fuel consumption by a factor of five or more.

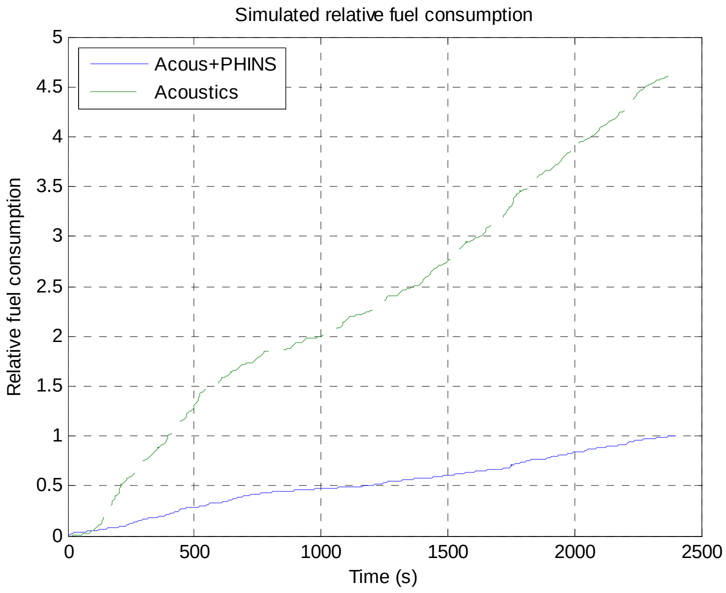

Figure 3 – Relative fuel consumption with/without INS in-fill

INS AND GPS

Whereas using INS with acoustics has obvious advantages, the use of INS with GPS (including differential GPS) is less clear. There are five possible benefits: replacement of differential corrections, detection of GPS failures, removal of erroneous 'jumps', ride-through for temporary outages, and reduced thrust demand implying lower fuel consumption in nominal operation. These possibilities are investigated in the following sections.

Replacement of differential corrections

In order to assess the possibility of replacing the differential corrections in the DGPS with an INS, data was logged on a stationary DGPS receiver in Rugby. The DGPS and GPS outputs were compared to give a differential correction, see Figure 4. It is clear from the figure that use of an INS for this purpose is impractical due to the frequency (< 0.01 Hz) of the differential corrections.

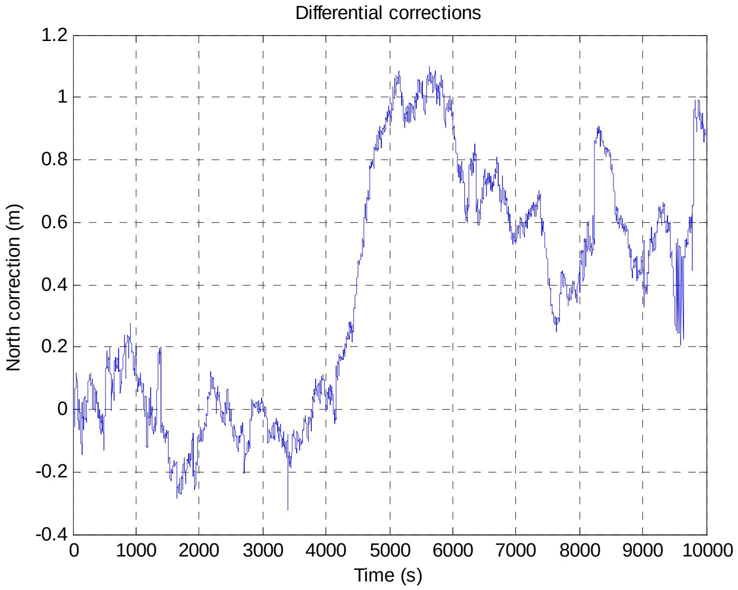

Figure 4 – differential corrections for stationary receiver

Detection of GPS failures and jumps

This section investigates the possibility of using INS for detection of GPS failures and removal of jumps. A common occurrence using (D)GPS is a jump in the position estimate. This can occur when the visible satellite constellation changes, either as the result of satellites rising or setting, or due to shielding from nearby objects. Typical examples of the latter include passing under a bridge or approaching a platform. These jumps are often negligible, but sometimes become significant. For example, Figure 5 shows a short jump of about 3 m and a short outage of about 15 s, which occurred in open water in the North Sea. The severity of a jump depends upon the operational situation of the vessel. Under most conditions a jump of 3 m is not problematic. During a close approach to a platform or other vessel, however, even small jumps can be 'uncomfortable'. The DP system includes algorithms for error detection, including detection of noise, jumps and drift (Stephens, 2004). Though these algorithms are sophisticated in their own way, the most reliable forms of error detection rely on comparison of two, three or more PMEs. The INS, as it is not based on a model but on real acceleration measurements, not only acts as a 'filter' on the DGPS measurements, but also rejects data during short term jumps, and fills-in for short outages. The next section examines the performance of the INS during long outages.

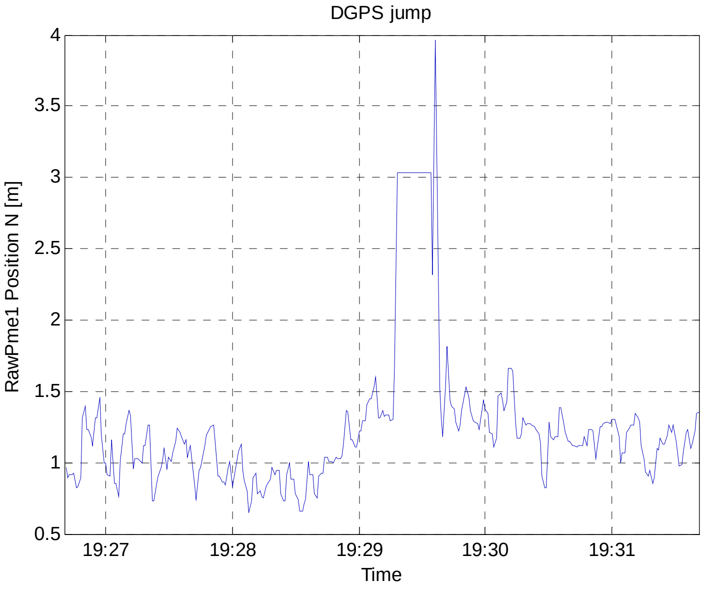

Figure 5 – DGPS jump in open water

Thrust demand and fuel consumption

Use of a high-quality INS in conjunction with a DGPS receiver reduces the level of high-frequency noise on the measured position. This has the effect of reducing the noise on the thruster demands, in the same way as the INS reduced the noise of the acoustics in the previous section. In the case of the DGPS, the effect is less dramatic since the noise is initially smaller. This reduction of noise is not the same as filtering: filtering introduces extra phase-lag into the control system whereas the INS is enhancing the position accuracy of the measurements without introducing lag.

Sea trials have been conducted on a 7000 t vessel utilizing a Converteam DP system and PHINS with DGPS. For part of the trial, the vessel was held in a constant position under full DP control with DGPS as the only PME, followed by a period with DGPS+PHINS as the only PME. Figure 6 shows the thruster demands for the X and Y axes during the two periods of operation. There is noticeably more noise on the DGPS only data.

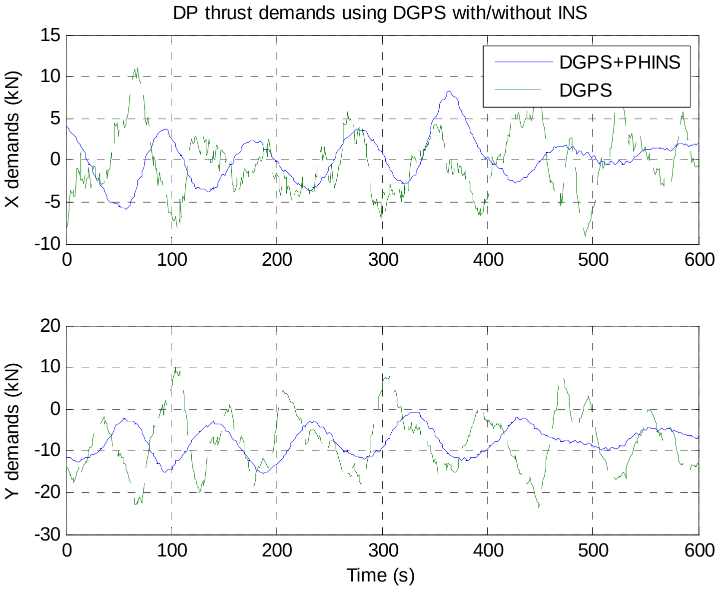

Figure 6 – thrust demand using DGPS with/without INS

In order to compare the expected fuel consumption with and without the INS corrections, the thrust demands were used to estimate a relative fuel consumption using the relationship $P \propto T^{1.5}$ as before. The results of the estimation, for the 10 min periods of the trial are shown in Figure 7. The system without the INS uses 40% more fuel than DGPS+INS.

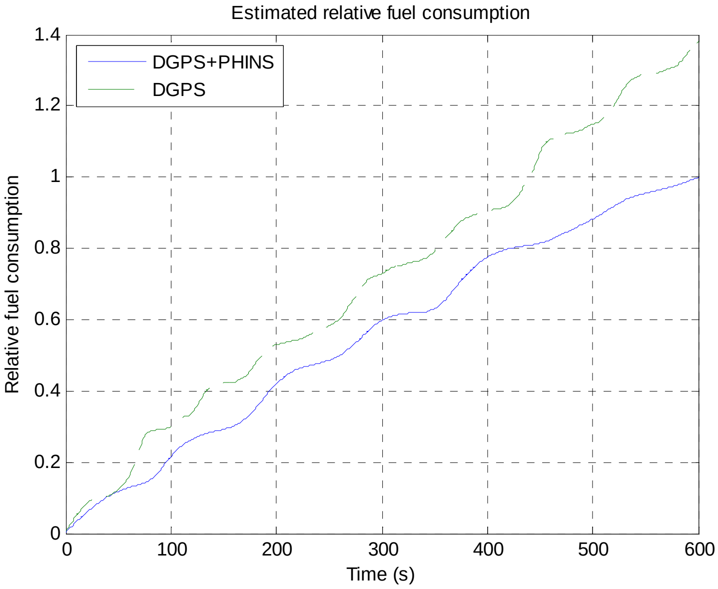

Figure 7 – estimated fuel consumption using DGPS with/without INS

OUTAGE RIDE-THROUGH

With sunspot activity increasing towards a maximum in 2012 or 2013, the likelihood of ionospheric scintillation will be increasing for the next few years. The Holy Grail for DP operators is an alternative method for measuring a vessel's position that is independent of the external influences. The usefulness of an INS during an outage of other PMEs depends on its drift. This drift is a function of inertial measurement unit (IMU) quality, calibration and correction. The short term accuracy of an INS derives from the accuracy of its accelerometers, while the longer term accuracy derives from the gyro accuracy (Gaiffe, 2006). The position is defined by the double integration of the accelerometers, so the position drifts according to the square of time and the stability of the accelerometers. .

Previously, outage data has been obtained for a stationary INS device (Paturel, 2004). Clearly, on a sea-borne vessel the INS will never be stationary. A series of tests were therefore carried out using a GPS unit and an INS in constant oscillatory motion, simulating bad weather. During the tests, the GPS input to the INS was removed at regular intervals and the positions of the INS and GPS compared over a period of 'outage'. Typical results from these tests are shown in Figure 8 and Figure 9. Figure 8 shows the evolution of the INS drift with time. The results compare well with previous investigations of stationary systems.

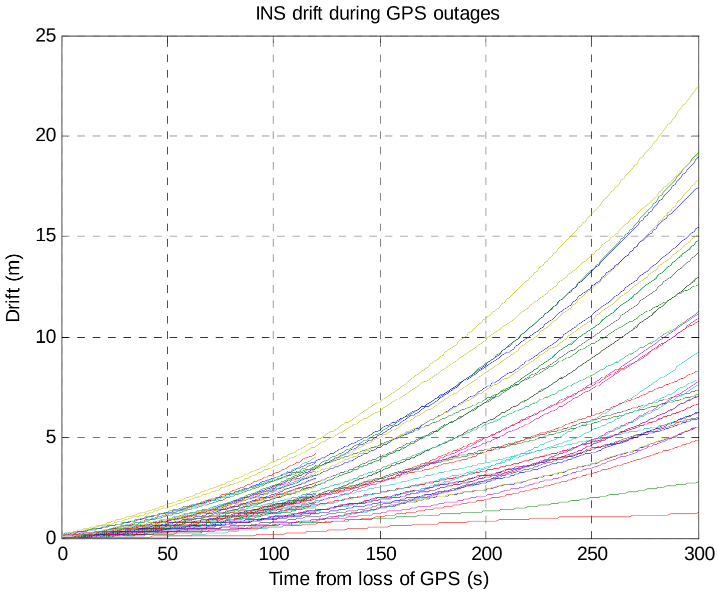

Figure 8 – evolution of INS drift during outages of 300 s and 120 s

Figure 9 shows the distribution of the errors after 120 s and after 300 s. The distribution of drift errors exhibit the shape of the Rayleigh distribution (Papoulis, 1984), which is characteristic of processes formed from the sum of squares of Gaussian distributed sources – because the drift distance is the sum of squares of the deviations in North and East directions.

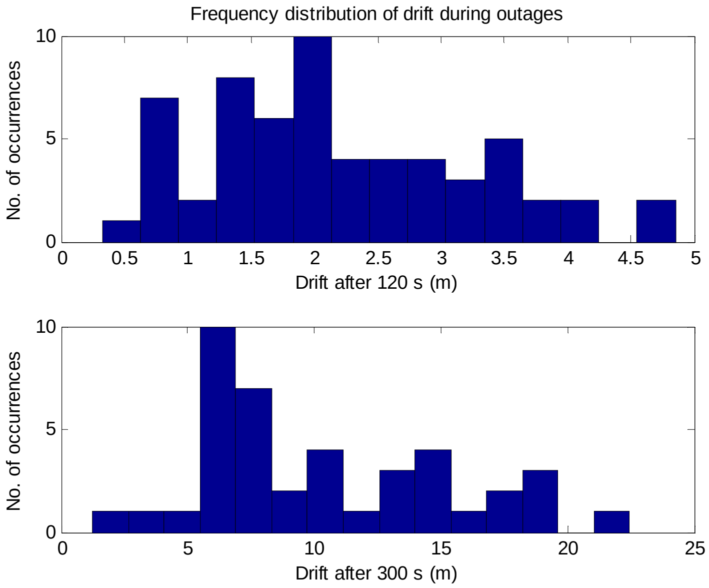

Figure 9 – distribution of INS drift after outages of 120 s and 300 s

How does the drift exhibited by the INS relate to expected motion of the vessel with no PMEs? To get an idea of the relative drifts of a vessel with no PMEs and one using only INS, we can estimate the force required to move a vessel off-station by the same amount as the observed INS drift. Taking the worst case from Figure 8, distance travelled $s = 22$ m after time $t = 300$ s, the equivalent constant acceleration, a, can be calculated from $a = 2s/t^2 = 4.9 \times 10^{-4}$ m/s^2. For a typical supply vessel of displacement $\nabla = 4000$ t, the force, F, required to achieve this acceleration would have been $F = \nabla a = 2.0$ kN. This is less than about 1% of the likely onboard thrust, suggesting that under moderate conditions, the vessel with no PMEs is likely to drift far more quickly than the INS. In addition, the drift of the INS is based on real physical measurements of the accelerations, not on a model which would become degraded in case of non-nominal conditions like bad weather with large waves, or breaking of cables or an umbilical that would be linked to the platform.

It should be noted that the intervals between the trials presented in Figure 8 – i.e. periods during which the DPGS was available again – were between 30 s and 300 s with no obvious difference between the two. This suggests that the self-alignment of the PHINS system is excellent, and the interval between outages is unlikely to be a problem in practical situations.

DP SYSTEM ARCHITECTURE

Due to its dependence on position measurements continually to estimate the errors in the accelerometers, we cannot treat an INS alone as an independent PME. It will always be dependent on one or more of the other PMEs. So, to keep independence between the PMEs, the INS should be tightly coupled with a single PME, for example the acoustic system, see Figure 10. The DP system treats the combination as a single PME. In this configuration it is important for information to be passed to the DP system concerning the quality of the INS/acoustic fix. For example, the DP should be warned if the INS loses the position measurements from the acoustic system. The same architecture can be utilized with the INS fed from a GPS.

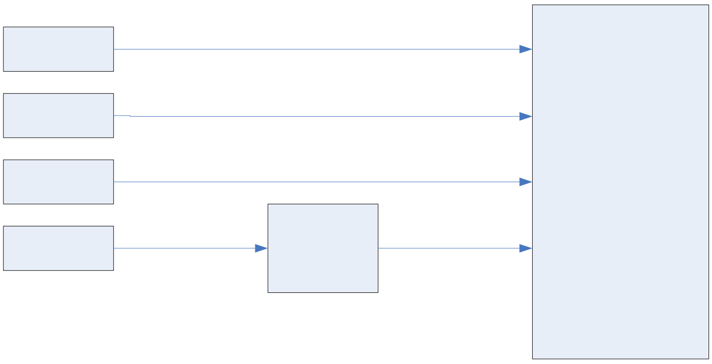

Figure 10 – normal architecture for INS with DP

A development of an alternative architecture is shown in Figure 11. The INS obtains position measurements from a number of PMEs, including GPS and acoustics. It is important that it uses only one of the position measurements at any one time to maintain its independence from the others. This architecture offers the main advantage of flexibility to the user, over the architecture of Figure 10. The user has the ability to choose between two possible configurations, depending on his application. For instance, if acoustics is required, the user can choose to use the INS+Acoustics configuration. Otherwise, he would select the INS+DGPS configuration.

The status messages sent to the DP must include enough information for the DP to determine the configuration of the PMEs and INS. The DP must be able to ensure that the PME used in the INS calculations is not used in its own position estimates. The architecture of Figure 11 is already feasible with existing equipment. The PHINS equipment includes multiple input ports to allow for this architecture.

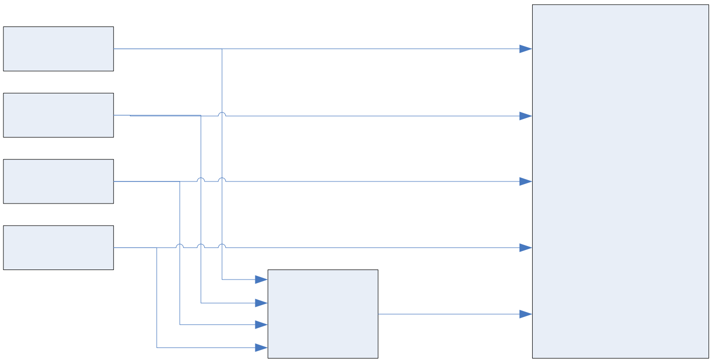

Figure 11 – first alternative architecture using multiple inputs to INS

A further enhancement would be to move to the architecture of Figure 12. In this configuration, the INS gets its position measurements from the DP system, which selects the measurements from one of the existing PMEs. The selection logic must continue to ensure that the INS measurements are independent of the other PMEs by excluding the PME-only measurements from the ship position estimation – relying on the INS corrected version. This configuration offers a number of additional benefits:

- The DP can automatically prevent rogue position measurements being passed to the INS by comparing multiple PME measurements.
- All the control/command of the full system during operation is accessible from the sole HMI of the DP system

GPS1

GPS2

Acoustics

Acoustics

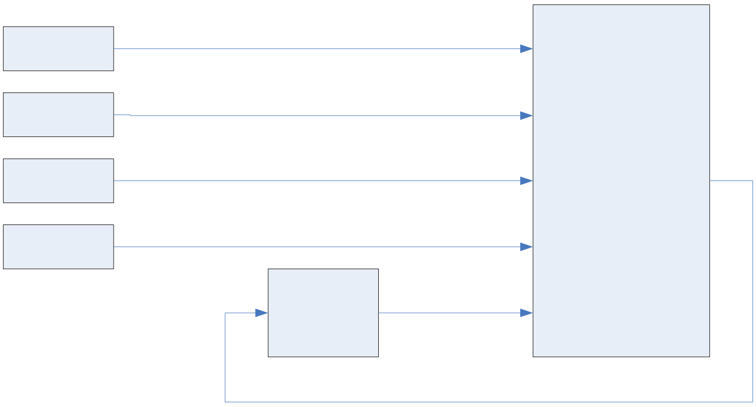

Figure 12 – proposed architecture for full integration of INS and DP

In this architecture, there is no loop, as the DP system acts as a switch – it sends only PME data to the INS, not the pooled position estimate. The INS software utilizes the estimated variances of the position measurements to maintain covariance estimates of the states. These will differ for different PMEs. It is necessary, therefore, to include information on the PME being used in the communication channel from the DP to the INS.

Acoustics with INS

With most acoustic systems on the market, the above architectures would require a PHINS as a standalone INS. There is one exception with the GAPS, which is an acoustic positioning system with an embedded INS, of the same class as the PHINS. This embedded INS can act as described above and thus can provide an INS output to the DP system. The GAPS would then be directly linked to the Converteam DP system, without a requirement for an additional INS.

Ease of use

Both PHINS and GAPS have a user friendly HMI. The integration is very much simplified as the PHINS is a standalone box with all computations performed internally, easy to set-up. The PHINS is IMO certified ('wheel-marked') which means that it can act as a gyrocompass and motion sensor, moreover of a high grade type. The GAPS is also an all-in-one calibration-free package that does not need an accurate and expensive hoisting system as the internal INS compensates for its own movements.

The ease of use of the INS is a major factor in its usefulness on board a vessel. Both PHINS and GAPS are easy to operate, and do not require expert personnel onboard. This equipment is now widely used, and operated by the vessel staff.

Finally, the PHINS is – and GAPS includes – an INS, which is very different from an IMU is the sense that all the computation is performed inside the equipment so that no raw data of the inertial sensors is output, making it safe against the risk of diversion of use, like missile technology. With respect to export rules – for operations abroad, or return to the factory for upgrade – the consequence is that PHINS and GAPS do not have all the limitations that face IMUs.

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CONCLUSIONS

The paper has investigated the use of an INS in DP operations. An INS can provide information about vessel position but due to natural drift it requires regular updates from another PME. The paper has investigated the performance of different applications including: INS with acoustics, INS with DGPS and ride-through of outages. In order to increase confidence in the usefulness of INS, tests have been performed at sea using acoustics, and under constant motion on land.

A combination of data from sea trials and post-processing using simulation has shown that an INS coupled with acoustics in deep-water can be used to extend the ping interval, thereby saving battery life, and reduce fuel consumption by filling-in between pings.

For INS with GPS, the replacement of differential corrections is not seen as a possibility, however, jumps and short outages in GPS reception are fairly common and could be removed by an INS.

The possibility of using INS to ride-through longer outages has been investigated using sea-trial data. Depending on the application and positioning accuracy, INS can provide a ride-through capability.

Finally, a number of possible system architectures have been discussed in order to obtain the most reliable and useful configuration for the INS. An architecture which allows the DP to select the reference input to the INS has been proposed.

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REFERENCES

Faugstadmo, J. E. and Jacobsen, H. P. (2003). “HAIN: An integrated acoustic positioning and inertial navigation system”, *MTS Dynamic Positioning Conference, 16-17 September 2003, Houston TX*.

Gaiffe, T. (2006). “From high technology to solutions: the experience of IXSea”, *web-based article, http://www.ixsea.com/pdf/2006-oceans-singapore.pdf*.

King, A. D. (1998). “Inertial navigation - forty years of evolution”, *GEC Review*, **13**(3), pp. 140-149.

Lewis, E. V. (1988). *Principles of Naval Architecture*, Society of Naval Architects and Marine Engineers, Jersey City, NJ, USA.

Papoulis, A. (1984). *Probability, Random Variables, and Stochastic Processes, 2nd edition*, McGraw-Hill, New York.

Parkinson, B. W. and Spilker, J. J. (Eds.) (1995). *Global Positioning System: Theory and Applications*, American Institute of Aeronautics and Astronautics, Washington DC, USA.

Paturel, Y. (2004). “PHINS, an all-in-one sensor for DP applications”, *MTS Dynamic Positioning Conference, 28-30 September 2004, Houston, TX*.

Stephens, R. I. (2004). “Aspects of industrial dynamic positioning: reality-tolerant control”, *IFAC Conference on Control Applications in Marine Systems, CAMS 2004, 7-9 July 2004, Ancona, Italy*, pp. 41-51.

Vickery, K. (1999). “The development and use of an inertial navigation system as a DP position reference sensor (IPRS)”, *MTS Dynamic Positioning Conference, 12-13 October 1999, Houston, TX*.