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Using Doppler Logs for Safer DP in Drilling

Richard I. Stephens, John C. Flint and Allan J. Meahan

ALSTOM Power Conversion Ltd (Rugby, UK)

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ABSTRACT

The paper describes the need for multiple, independent sources of measurement for use in dynamic positioning (DP). It examines some of the problems of existing solutions and proposes using Doppler log velocity measurements as an alternative, independent source of position information. The inclusion of the velocity measurements into the Kalman filter formulation is outlined and some of the problems that had to be overcome are described. Simulation results are presented to show the potential of the proposal and these are supported by data gathered from a full-scale vessel.

INTRODUCTION

The move to deeper and deeper water has presented major problems for operators of dynamic positioning (DP) drilling and support vessels as the available position measuring equipment (PME) is stretched to its limits. Acoustic systems become noisier with longer update periods, taut-wire systems become untenable. More and more reliance is placed upon GPS and DGPS. This has presented problems when disturbances in the ionosphere have disabled GPS systems (Bray, 2005).

There is a need for new measurement systems that are independent of the traditional PMEs. The alternative presented in this paper is to incorporate velocity measurements from Doppler logs, which are utilised within a Kalman filter (KF) to maintain an estimate of position. The KF formulation allows the Doppler to be used either in conjunction with other PMEs (for example, to fill in the gaps of a slowly updating acoustic system, or to assist in the reduction of noise) or alone when all other PMEs fail. This latter use could prove crucial in an emergency allowing the DP to continue safely for many minutes with velocity measurements only and is the main focus of the remainder of the paper.

PROBLEM FORMULATION

Safe operation in DP relies upon measurement of the vessel position and heading at all times. In order to ensure that this is true, even under fault conditions, all measurement systems include redundancy. Physical redundancy requires the replication of equipment to ensure that a single failure of any piece of equipment will not result in complete failure of the overall system, allowing faulty equipment to be by-passed using the redundant hardware. The parallel redundant systems must be independent – i.e. no single failure mode should be capable of disabling the overall system. For measurement of heading this independence can be achieved by installing multiple gyrocompasses, since no failure of an individual unit will affect the others.

Whilst the gyrocompass offers a compact, reliable and accurate measurement of vessel heading, independent of outside disturbances, the measurement of position has proved to be more complex.
The provision of independent position measurements depends upon the location and operation of the vessel. For stationary operation in water depths up to about 1000 m multiple taut-wire systems provide independent redundant feedback of vessel position. No single failure can disable all the taut-wires. However, for many vessels, taut-wire is not an option; for example, drilling vessels have to operate in increasingly deep water.

Acoustic PME systems suffer from a number of disadvantages. In deep water their measurements can be noisy and the interval between measurements increases, leading to loss of positioning accuracy. Multiple acoustic systems cannot be considered independent of each other since they all rely on the integrity of the same medium – the water. Deployment and recovery of acoustic beacons are an unavoidable burden on fast turn-around times.

The global positioning system (GPS) and differential GPS (DGPS) now dominate the position measurement market due to their cost, convenience, accuracy and size. They do, however, share a single mode of failure and ionospheric perturbations, particularly in tropical regions, have resulted in complete loss of GPS measurements for significant periods (Bray, 2005).

INTEGRATION OF VELOCITY MEASUREMENTS INTO POSITION ESTIMATES

Additional information about a vessel's position can be obtained by measuring its velocity in surge and sway using a dual-axis Doppler log. Doppler logs are relatively cheap and compact. They operate by measuring the Doppler shift of high-frequency acoustic signals reflected either from the sea-bed (known as "bottom lock") or from particles in the water (known as "water lock"). The bottom lock feature is typically available for water depths up to approximately 200 m. The water lock feature measures the vessel speed relative to the water at some distance (up to about 25 m) below the hull.

The ALSTOM DP system incorporates KF technology to provide estimates of vessel position and velocity whilst rejecting measurement noise and high-frequency first order wave motions (Stephens *et al*, 1994). The system merges all valid, available and selected position measurements. In order to utilise measured velocities they must be incorporated into the estimate from the KF. This is achieved by defining within the KF algorithm an alternative measurement type. The next section describes the basic KF arrangement and shows how to incorporate velocity measurements.

Basic KF equations

The basic KF equations (see, for example, Åström and Wittenmark, 1990) are based on a discrete state space model of the ship as follows:

$$\mathbf{x}(t+\tau) = \mathbf{\Phi x}(t) + \mathbf{\Gamma u}(t) + \mathbf{w}(t) \qquad (1)$$

$$\mathbf{y}(t) = \mathbf{Hx}(t) + \mathbf{v}(t) \qquad (2)$$

Where $\mathbf{x}(t)$ is the state vector at time t, $\mathbf{u}$ is a vector of control inputs and feed-forward forces, $\mathbf{y}$ is a vector of measured outputs. τ is the sampling period whilst $\mathbf{\Phi}$, $\mathbf{\Gamma}$ and $\mathbf{H}$ are matrices defining the transitions of the state vector. $\mathbf{w}$ and $\mathbf{v}$ are noise processes acting on the states and the output respectively. $\mathbf{w}$ and $\mathbf{v}$ are assumed to be Gaussian with zero mean.

The KF method is based on a cycle of prediction followed by correction. At each time step the following equations, based on the model equations (1) and (2) above, are used to extrapolate the state $\mathbf{x}$ forward and generate a prediction of $\mathbf{y}$.

$$\hat{\mathbf{x}}^*(t+\tau) = \mathbf{\Phi}\hat{\mathbf{x}}(t) + \mathbf{\Gamma u}(t) \qquad (3)$$

$$\hat{\mathbf{y}}(t) = \mathbf{H}\hat{\mathbf{x}}^*(t) \qquad (4)$$

Where $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ are the estimated state and measurement vectors respectively. $\hat{\mathbf{x}}^*$ is an intermediate state vector following the extrapolation. When a measurement of position is available, the predicted position, $\hat{\mathbf{y}}$, is compared with the measurement and the states corrected as follows:

$$\mathbf{e}(t) = \mathbf{y}(t) - \hat{\mathbf{y}}(t) \qquad (5)$$

$$\hat{\mathbf{x}}(t) = \hat{\mathbf{x}}^*(t) + \mathbf{L}(t)\mathbf{e}(t) \qquad (6)$$

$\mathbf{e}$ is a vector of errors between the measurements and estimates. $\mathbf{L}$ is a matrix of update gains (usually known as Kalman gains) which may be time varying.

The formulation of the above equations allows for vectors of inputs, **u,** and measurements, **y,** so that it is straightforward to include a number of measurements from different measuring equipment. This provides a mechanism for including velocity measurements into the Kalman filter. The measurement vector, **y**, and error vector, **e**, are extended to include velocity measurements. The measurement transition matrix, **H**, must have rows added to form an estimated velocity output, whilst the Kalman gain matrix, **L**, requires extra columns for the new measurements (Stephens *et al*, 1994).

The model also includes extra states within $\hat{\mathbf{x}}$ in order to account for the dynamics of the measuring instrument, requiring augmentation of $\mathbf{\Phi}$, $\mathbf{\Gamma}$, **H** and **L.** In the event of a loss of all measurements, no correction is possible and the estimates revert to so-called “model control”, in which only the prediction stage (i.e. equations (3) and (4)) is performed.

Drift estimation

A Doppler log in water lock is likely to be affected by a current or tide, leading to an offset on the measured velocity. If no other PME is available this leads to a drift in the estimated position proportional to elapsed time. In order to correct for this source of error, the offset on the velocity measurement must be estimated within the system, in which case one of two methods may be employed. The first is to augment the KF state vector, $\mathbf{x}$, to include a drift term for each Doppler log on the vessel. The KF model matrices $\mathbf{\Phi}$, $\mathbf{\Gamma}$ and $\mathbf{H}$ must also be extended. The Kalman gain matrix, $\mathbf{L}$, also requires recalculating, the tuning of which is critical to ensure that the drift estimation is performed in a satisfactory manner. The alternative method of drift estimation is to form a separate estimator for each Doppler log, which compares measured and estimated velocities. It should be noted that, for either method, estimation of the velocity offset is only possible if other PMEs are present. Once all other PMEs are lost, the velocity offsets are no longer distinguishable from vessel motions and the estimation of velocity offsets must be frozen.

ACHIEVING INDEPENDENCE

As noted above, safe DP relies upon multiple, independent position measurement systems, in the sense that no single mode of failure can affect all measurement devices. The definition of independence clearly excludes so-called “tightly coupled” systems in which, for example, and inertial navigation system corrects its own drift using an integrated (D)GPS receiver.

The previous section discussed the requirement for identification of a velocity offset for Doppler logs in water lock, utilising other PMEs to differentiate between effects of current and vessel motion. There is clearly a danger of introducing dependency between the Doppler log and the other PMEs through the offset estimation. Independence can be achieved, however, by ensuring that:

1. velocity offsets are estimated in the DP system, not the Doppler log itself (i.e. the measurement systems must not be tightly coupled);
2. fault detection is included in the DP system to reject faulty measurements;
3. adequate fault-tolerant strategies are included in the DP system to ensure that a fault on a PME does not corrupt the velocity offset estimates (e.g. Stephens, 2004).

The best place to detect measurement faults, and to combine the measurements, is in the DP system itself, since the DP system incorporates a model of the vessel motion, including effects of thrust and environment not available to individual sensors.

SIMULATION RESULTS

Simulation has been used to verify the algorithms described above. The results presented here are a sample of the simulation testing performed. The results illustrate the expected improvement from the use of Doppler logs. Monte Carlo simulation studies have been performed to demonstrate the efficacy of the technique. In the Monte Carlo method multiple simulation runs are performed with different starting conditions, selected randomly from a specified range.

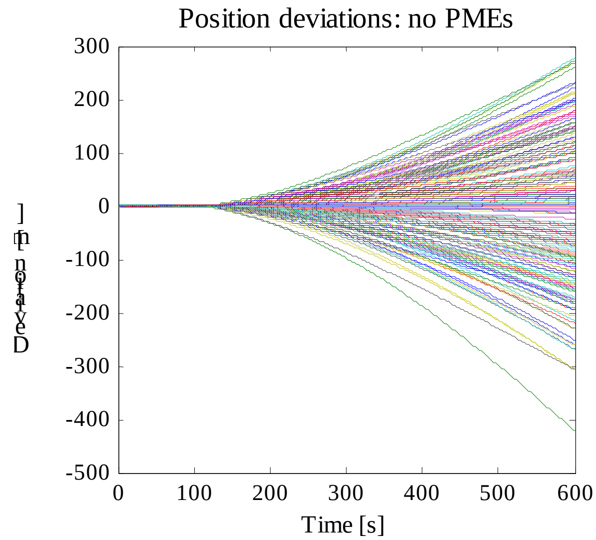

Figure 1 – loss of all PMEs after 100 s

For each simulation run, the Monte Carlo algorithm selected random wind velocity and heading and current velocity and heading. Figure 1 shows the results of 100 simulation runs on a vessel under DP control. After 100 s the only position PME was lost leaving the vessel in model control. The figure shows that the vessel drifts from its aim position, reaching a maximum position deviation, for this case, of greater than 400 m error after a further 500 s. The deviations after the loss of the PME are due to the PME noise and weather effects causing small changes in the estimate of vessel velocity and environmental force.

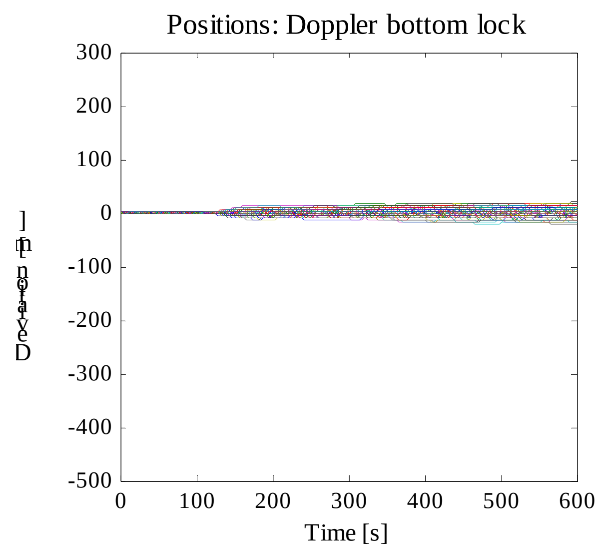

Figure 2 – Doppler log only after 100 s

At the time of the loss of measurements the estimated value of environmental force is frozen – since there is no further information available. Since there is some randomness in the estimate, there is a chance that this frozen value is far enough from the true environmental force to cause the vessel to drift. It should be noted that the maximum drift rate will depend on a number of factors, including the weather conditions, the noise on the PMEs, the level of filtering and the gains selected by the DP operator. The deviations from target position would be expected to be significantly larger if the weather conditions changed after the loss of the position PME.

Measurement type	Position error std. dev. (m)
DGPS	1.2
Bottom lock	7.7
Water lock	10.3
None	138.8

Table 1 – position error standard deviations for different measurement types after 500 s simulation

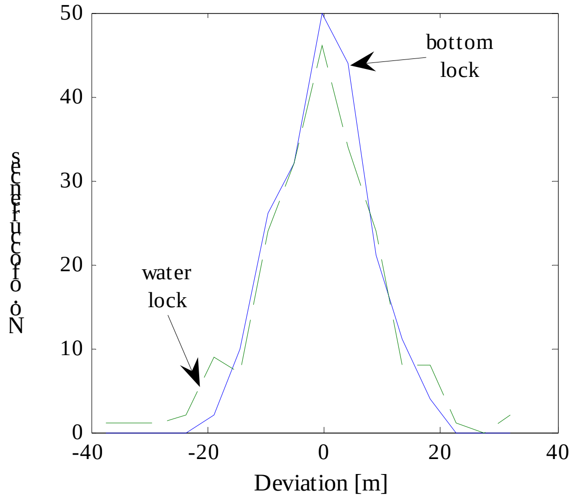

Figure 3 – distribution of position errors after 500 s using Doppler log measurements only

Figure 2 shows the results of the same 100 simulations, run with a Doppler log available in addition to the position PME. Again, the position PME is lost after 100 s but the Doppler log remains available after the loss of the position measurement. The figure shows that the vessel remains in the region of the target, its maximum position deviation being about 20 m. Comparing Figures 1 and 2 shows the dramatic improvement in station-keeping possible with bottom lock Doppler measurements.

Figure 3 shows comparisons of the distribution of position errors for DP operations using only a Doppler log in both bottom lock and water lock. The results were obtained from further Monte Carlo type simulations consisting of 200 runs each. The figure shows that the position errors after 500 s are comparable between bottom lock and water lock. This is important since it is expected that water lock will be necessary for the majority of drilling applications due to the likely depth of water.

Table 1 shows a comparison of the standard deviations of position error following 500 s of simulation using various measurement types. It shows that the expected performance of DP using a Doppler log is an order of magnitude better than with no measurements after 500 s, whilst water lock and bottom lock are comparable in performance.

FULL-SCALE TRIAL RESULTS

Full-scale trials of a DP system operating using Doppler logs will be conducted during 2005. At the time of writing the vessel concerned is undergoing commissioning. Figure 4 shows data from the vessel comparing the outputs of the KF position estimate in three different conditions: i) no measurements, i.e. model control, ii) measured velocities from the Doppler log in water lock mode; iii) position measurements from DGPS. The trial was run for 700 s during which time the Kalman position using Doppler data deviated from the true position (measured using DGPS) by only 10 m. In the same period, the estimate with no PMEs diverged to 150 m from the actual.

The results shown are typical of a number of short trials conducted during initial commissioning. They show that the Doppler log can significantly improve position keeping in the absence of other measurement systems. More extensive trials will be conducted soon.

CONCLUSIONS

Safe DP relies upon effective redundancy of measurement systems. This redundancy is achieved by having available multiple, independent measurement systems.

Dual axis Doppler logs can contribute to the available measurement pool to provide greater reliability for short-to-medium term outages (at least up to 10 minutes) of other systems even in deep water. Independence of the Doppler log can be achieved by provision of adequate fault-tolerant measures within the DP system.

Simulation studies have shown the viability of the concept. Full-scale data has also been presented suggesting that the use of Doppler logs during PME outages can achieve adequate position accuracy for many applications, and an order of magnitude better accuracy than with model control.

A DP system with fully integrated Doppler logs as measurement systems is currently undergoing final commissioning.

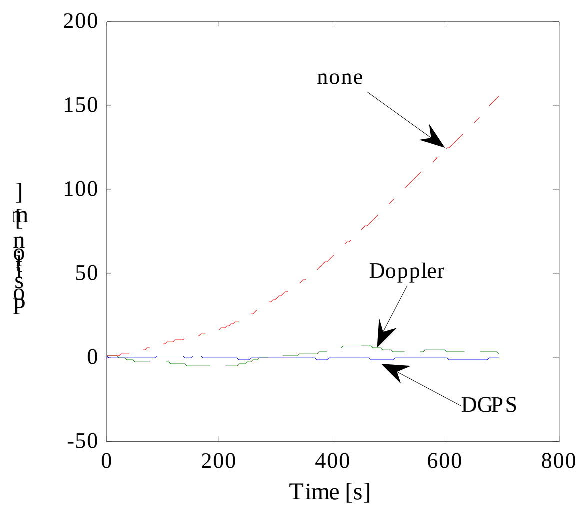

Figure 4 – ship position estimates using logged data from full-scale trials with: i) no measurements; ii) Doppler only; iii) DGPS only

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