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INERTIAL SENSORS FOR RISK-BASED REDUNDANCY IN DYNAMIC POSITIONING

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ABSTRACT

In this paper we present an alternative configuration of sensors, position and heading reference systems for dynamically positioned (DP) vessels. The approach uses a sensor structure based on low-cost inertial measurements units (IMUs), satisfying fault tolerance against single-point failures that is at the essence of the IMO guidelines for both DP class 2 and 3 vessels. Recent results have shown that dual-redundant position and heading reference systems are sufficient to prevent loss of position within some well-defined time horizons by exploiting sensor fusion of the reference systems and triple-redundant MEMS-based IMUs. These IMUs also function as Vertical Reference Units (VRUs), since vessel motions is obtained using the same IMU configuration and sensor fusion framework. In this proposition, the acceleration measurements provided by the IMUs make wind and other force sensors unnecessary, except possibly for an advisory role. The proposed framework has the potential to significantly reduce the cost of dynamic positioning systems without compromising safety.

NOMENCLATURE

$\{b\}$	BODY coordinate frame
$\{t\}$	Tangent frame equivalent to North East Down (NED) where $\{t\}$ is Earth fixed and rotates with the Earth rate
$\{e\}$	Earth Centered Earth Fixed coordinate frame
$\{i\}$	Inertial coordinate frame
p^t_{tb}	$\in \mathbb{R}^3$ Position in $\{t\}$ frame
v^t_{tb}	$\in \mathbb{R}^3$ Linear velocity in $\{t\}$ frame
ω^b_{ib}	$\in \mathbb{R}^3$ Angular rate of the vessel($\{b\}$ frame) relative the inertial frame in the BODY frame, given in the BODY frame
f^b_{ib}	$\in \mathbb{R}^3$ Spesific force of the vessel($\{b\}$ frame) relative the inertial frame in the BODY frame, given in the BODY frame
ϕ, θ, ψ	Euler angles: Roll, pitch, yaw
$R(\psi)$	$\in SO(2)$. Rotation matrix: For rotations about the z-axis, relating the BODY and the NED frame
R^t_b	$\in SO(3)$ Full rotation matrix, describing the attitude between the $\{b\}$ and the $\{t\}$ frame.
r^b_b	$\in \mathbb{R}^3$ Leverarm from vessel CO to given position reference system (PosRef)
p^t_x	North position components given in $\{t\}$ (similar to NED)

p^t_y East position components given in $\{t\}$ (similar to NED)
u^b_{tb}, v^b_{tb} Surge and sway velocity
r Yaw rate
$\tau_\star$ Generalized force vector
M Mass matrix. $M > 0 \in \mathbb{R}^{3\times 3}$.
D Linear damping matrix. $D > 0 \in \mathbb{R}^{3\times 3}$.
dGNSS Differential Global Navigation Satellite Systems
DP Dynamic Positioning
FDI Fault Detection and Isolation
HPR Hydroacoustic Position Reference
IMO International Maritime Organization
IMU Inertial Measurement Unit
INS Inertial Navigation System
MEMS Micro-electrical-mechanical System
PosRef Position Reference
VRS Vertical Reference Sensor
VRU Vertical Reference Unit
ZUPT Zero Velocity Update

INTRODUCTION

The International Maritime Organization (IMO) have issued guidelines for vessels with dynamic positioning (DP) systems, [1], to reduce the risk of loss of position during DP operations. Classification societies have defined class notations based on these guidelines. The DP classifications are dependent on vessel type, operation and the potential consequences in the event of loss of position. These range from equipment class 1 to 3, while some societies also operate with equipment class 0.

The general functional requirement is that single failure in an active component should not result in loss of position. This is handled by redundancy in all active components, where redundancy, according to [2], is defined as:

> *Redundancy*. The ability of a component or system to maintain its function when one failure has occurred. Redundancy can be achieved, for instance, by installation of multiple components, systems or alternative means of performing a function.

For equipment class 2 and 3, the following main rules are given by MSC/Circ. 645, [1]:

> Equipment class 2: Redundancy in all active components.
> Equipment class 3: Redundancy in all active components and physical separation (A.60) of the components.

Equipment class 1 (and 0) allows for loss of position in the event of a single failure. Therefore, these classes will not be dealt with further in the paper. A more detailed description is given in Tab. 1, where class notations from DNV GL, American Bureau of Shipping (ABS) and Lloyds Register (LR) are given. Concerning the sensors system on a DP vessel, both DP notations related to equipment class 2 and 3 often implement the redundancy requirement by enforcing a triple-redundancy requirement related sensor to installation. In the authors' opinion, this practice has so far not taken advantage of the full potential of MEMS inertial sensors, obtained from recent developments, and the knowledge of upsides and downsides with the different standard onboard sensors. The triple-redundancy requirements may also in certain circumstances impair robustness and safety since the potential downsides outweighs the potential upsides. Especially so related to the wind sensor where the conclusions from [3], state that using the wind sensor is not essential for maintaining positing and, in fact, that using wind-feed-forward control can be detrimental in stationkeeping.

This paper proposes an alternative sensor configuration to that of today's state-of-the-art class notations. The configuration has low-cost redundant MEMS IMUs at its center. With this structure, the redundant IMUs, with appropriate software, have the potential to replace existing sensor solutions. In addition, dual-redundant PosRefs and gyrocompasses are deemed sufficient to maintain position and heading. The latter is due to FDI of the PosRefs and gyrocompases obtained by exploiting the redundant IMUs and estimators. Moreover, the sensor structure is compliant with the main principle of both equipment class 2 and 3; no single point of failure in an active (sensor) component shall results in loss of position. With IMUs, all accelerations, induced by forces affecting the vessel, are measured directly by accelerometers. Therefore, the wind sensors can be circumvented without impeding the DP control performance. Furthermore, the industry-standard VRU solutions can also be replaced since the vessel motions are obtained using the same redundant-IMU configuration and sensor fusion. All in all, the proposed sensor configuration has the potential to significantly reduce the cost of dynamic positioning systems without compromising safety.

SENSOR AND CONTROL SYSTEMS

DP Sensor Systems

Several types of sensors are applied on a DP vessel. IMO and the classification societies differentiate between PosRef systems and (external) vessel sensors. PosRefs provide localization of the vessel, local position relative some known point or global positioning, and can be based on dGNSS, e.g. dGPS, dGLONASS, dBeiDou, HPR, optical (e.g. Fanbeam, CyScan) and microwave (RadaScan, Radius). The other vessels sensors consist of three main types:

> **Gyrocompasses**: Providing heading measurements, ψ.
> **Wind sensors**: Providing measurements of wind speed and direction. With these signals, wind forces and moments are calculated using wind coefficients and a model of the wind projection area.
> **VRUs/VRSs**: Provide roll (ϕ), pitch (θ) and sometimes heave. These signals are primarily utilized for leverarm

TABLE 1. DP Classifications

Description	**IMO**	**Class notations**		
Related to automatic and manual position and heading control	**DP Class**	**DNV GL**	**ABS**	**LR**
In case of single fault excluding loss of a compartment. Two independent computer systems. Specified maximum environmental conditions.	Class 2	DPS 2 DYNPOS-AUTR	DPS-2	DP (AA)
Single fault including loss of a compartment due to fire or flood. Two (or more) independent computer systems. Extra back-up system separated by A.60 class division). Specified maximum environmental conditions.	Class 3	DPS 3 DYNPOS–AUTRO	DPS-3	DP (AAA)

compensation of PosRefs to a given point of the vessel/center of orientation (CO);

$$p^t_{\text{CO}} = p^t_{\text{PosRef}} - R^t_b(\phi, \theta, \psi) r^b_b. \tag{1}$$

DP Control System

The sensors are related to the control problem illustrated with the simplified vessel model, [4],

$$\dot{\eta} = R(\psi)\nu \tag{2}$$

$$M\dot{\nu} = -D\nu + \tau_{\text{envir}} + \tau_{\text{DPc}} \tag{3}$$

where $\eta := (p^n_{\text{CO},x}, p^n_{\text{CO},y}, \psi)^\intercal$ and $\nu = (u^b, v^b, r)^\intercal$ are the vessel's horizontal generalized position and velocity, respectively. Furthermore, the generalized environmental forces on the vessel are represented by

$$\tau_{\text{envir}} = \tau_{\text{current}} + \tau_{\text{waves}} + \tau_{\text{wind}} + \tau_{\text{ice}}, \tag{4}$$

where $\tau_{\text{DPc}} = -\hat{\tau}_{\text{wind}} + \tau_{\text{DP}}$ is the vessel controller induced force. The forces obtained from the wind sensors, $\hat{\tau}_{\text{wind}}$, can be utilized in wind-feed-forward control. In addition, the DP controller signal, τ_{DP}, is used to compensate for current, wave drift and possibly ice forces and moments.

Inertial Measurement Units

An IMU provides measurements of tri-axial angular rate and specific force, provided by rate gyros and accelerometers, respectively, corrupted with noise and other error sources such as biases:

$$\omega^b_{\text{IMU}} = \omega^b_{ib} + b_{\text{gyro}} + \varepsilon_{\text{gyro}} \tag{5}$$

$$f^b_{\text{IMU}} = f^b_{ib} + b_{\text{acc}} + \varepsilon_{\text{acc}}. \tag{6}$$

Both types of error sources are mitigated with estimators and observers which are well established [5–7] in the literature.

Inertial Navigation System (INS)

An inertial navigation system can be utilized to estimate the vessel's position, velocity and attitude (PVA). In addition, the inertial sensor biases are estimated by utilizing aided INS. Aided INS is implemented with some sensor fusion software based on e.g. extended Kalman filters (EKF), [6, 7] or nonlinear observers (NLOs), see [8, 9] and the references therein.

The INS can be realized by mechanizing the strapdown equations based on the IMU measurements; see e.g. [6]. For DP, this can be done by e.g. choosing a tangent representation of the NED frame, taking the form

$$\dot{p}^t_{tb} = v^t_{tb}, \tag{7}$$

$$\dot{v}^t_{tb} = -2S(\omega^t_{ie})v^t_{tb} + R^t_b f^b_{ib} + g^t_b, \tag{8}$$

$$\dot{R}^t_b = R^t_b S(\omega^b_{ib}) - R^t_b S(\omega^t_{it}), \tag{9}$$

where $\omega^t_{ie} = \omega^t_{it}$ is the angular rate of $\{t\}$ relative $\{i\}$.

CURRENT DP SENSOR CONFIGURATIONS AND CLASSIFICATIONS

The current DP sensors classification are based upon MSC/Circ. 645 by IMO, [1]. Related to PosRef, MSC/Circ. 645 states:

1. Position reference systems should be selected with due consideration to operational requirements, both with regard to restrictions caused by the manner of deployment and expected performance in working situation.
2. For equipment classes 2 and 3, at least three position reference systems should be installed and simultaneously available to the DP-control system during operation.

TABLE 2. Current Sensor configuration classifications required by DNV GL [2]

Sensors		Class 2	Class 3
PosRef		3	3
External sensors	Wind	3(2)[a]	3(2)[a]
	Gyro compass	3	3
	VRS/VRU	3(2)[b]	3

[a] Three for DYNPOS–AUTR and AUTRO. Two for DPS 2 and DPS 3.

[b] Three for DYNPOS–AUTR. Where necessary for the correct functioning of position reference systems, at least three vertical reference sensors are to be provided for notation DPS 2

3. When two or more position reference systems are required, they should not all be of the same type, but based on different principles and suitable for the operating conditions.
4. The position reference systems should produce data with adequate accuracy for the intended DP-operation
5. The performance of position reference systems should be monitored and warnings provided when the signals from the position reference systems are either incorrect or substantially degraded.
6. For equipment class 3, at least one of the position reference systems should be connected directly to the back-up control system and separated by A.60 class division from the other position reference systems.

Furthermore, the IMO guidelines have put fourth the following guidelines related to the remaining vessel sensors:

1. Vessel sensors should at least measure vessel heading, vessel motions, and wind speed and direction.
2. When an equipment class 2 or 3 DP-control system is fully dependent on correct signals from vessel sensors, then these signals should be based on three systems serving the same purpose (i.e. this will result in at least three gyrocompasses being installed).
3. Sensors for the same purpose, connected to redundant systems should be arranged independently so that failure of one will not affect the others.
4. For equipment class 3, one of each type of sensors should be connected directly to the back-up control system and separated by A.60 class division from the other sensors.

DNV GL has, based on these guidelines, created classifications related to the necessary amount of sensors as presented in Tab. 2. The resulting sensors structure is illustrated in Fig. 1. This structure has the benefit of being intuitive where consistent triple redundancy makes it easy to perform FDI if one sensor fails, since the two remaining exclude the erroneous one with majority voting. However, this is not optimal since the specific force and angular rate inertial sensors contained in the VRUs are not exploited in the FDI of the PosRefs and gyrocompasses. Moreover, usage of the wind sensors is non-optimal and potentiality detrimental for stationkeeping capabilities, [3]. Here, taking advantage of contemporary high-quality MEMS sensors, with a relatively low cost, they can serve as an alternative in the force calculations, [2, Appendix B], currently done by the wind sensor. The benefit of the inertial sensors are that regardless of the wind speed, direction and distribution, the induced vessel's accelerations and angular velocities are measured directly, whereas for the wind sensors, the respective locations are important to obtain the correct forces. The wind force calculations are also sensitive to errors in the wind coefficients, projection area in addition to the speeds and directions measured. Moreover, the triple-redundant sensor requirement is also a cost driver of DP systems.

TABLE 3. Proposed sensor structure for DP

Sensors	Class 2	Class 3
PosRef	2	2[a]
Gyro compass	2	2[a]
MEMS IMU	3	3[a]
Wind[b]	0	0

[a] Minimum 1 is subjected to A.60 class division for fire and flooding protection.

[b] Zero for positioning (wind-feed-forward control). One for weather predication and satisfying IMO Circ. 465. is applicable.

PROPOSED SENSOR CONFIGURATION

The proposed sensor configuration, based on triple-redundant IMU measurements and dual-redundant PosRefs and gyrocompasses, is given in Tab. 3 and depicted in Fig. 2. In contrast to the current class notations, the wind sensors are removed. This design is based upon applying sufficiently many inertial sensors such that any single fault in any of the IMUs' axis measurements are detectable and identifiable.

Inertial measurements that are deemed fault-free are weighted/averaged and then utilized in an FDI framework used to validate PosRefs and gyrocompasses. In addition to the inertial sensors and dual PosRefs and gyrocompasses, the FDI framework is based on redundant estimators. The weighted/averaged IMU measurements also form the basis for obtaining the inherit VRU solution, by estimating roll, pitch and heave, without any use of distinct VRUs. In addition, since specific force and angu-

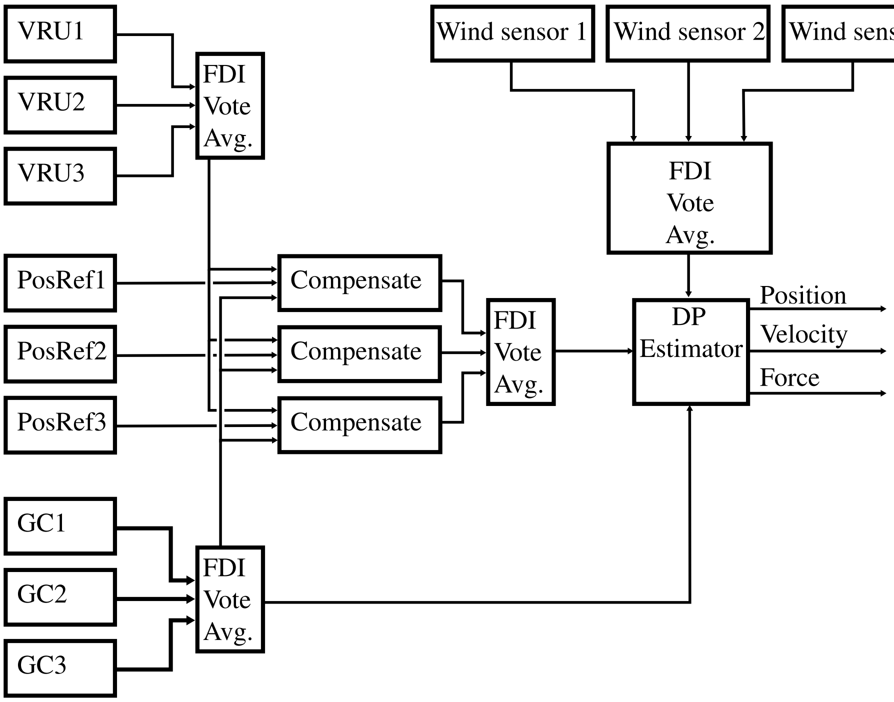

FIGURE 1. Current sensor structure of PosRefs, gyrocompasses (GC), VRUs and wind sensors. It is also common to use VRU*i* to motion compensate PosRef*i* and not use the averaged roll and pitch signals .

lar rate measurements are available, an INS can be sufficient as DP estimator, and vessel-model-based DP estimator is not necessary. This claim is supported by developments of INS-based wave filters [10], where wave filters are utilized to prevent the oscillatory wave-induced motions to be considered by the control system, [11].

Redundant IMUs instead of VRUs

State-of-the-art redundant-VRU FDI is based on signal processing of the respective roll and pitch outputs (ϕ_1, ϕ_2, ϕ_3 and $\theta_1, \theta_2, \theta_3$) before providing the DP system with averaged roll and pitch estimates (ϕ_{avg} and θ_{avg}). These, together with the averaged gyrocompass measurements are utilized for leverarm compensation of PosRefs. The VRUs are based on some type of inertial sensors, MEMS or other type of inertial sensing technology. Therefore, we propose that the averaging is performed at the IMU level [12] before estimating the VRU solution, providing roll, pitch and heave estimates, still based on redundant sensing. However, now only one set of VRU-output estimates are provided. The VRU solution is obtained from the INS, depicted in Fig. 2. The VRU solution can be carried out with or without aiding from PosRefs, and the former is done in [8].

In order to ensure that IMU faults are detected and isolated, a parity-based FDI can be applied [12], which is well established for redundant inertial sensing [13]. Redundancy in just the inertial sensors at the input level of the INS or in both the inertial sensing and in the output of the attitude estimators can be applied in order to achieve appropriate FDI. The latter approach is based on attitude averaging, taking in account the topological constraint of estimates on $SO(3)$. In addition, the result of [12] also indicate that averaged accelerometers are beneficial for heave estimation performance.

Dual vs. Triple-redundant PosRefs and Gyrocompass

The idea behind triple redundancy in PosRef systems and vessel sensors is that if one of them fails, it is straightforward to identity the faulty sensor by voting algorithms. Also, for performance, the combined, weighted output of three systems surpasses that of a single system. However, especially for PosRefs, common mode faults and disturbances reduce the advantages that may be reaped from such configurations if identical systems are used; the average of three false outputs is still false.

For position reference systems in DP, there are cases where one might not be able to utilize three separate systems operating by different principles. In deep waters, it is conceivable that only GNSS and HPR are available. Adding a third position reference then means adding a second one of the existing types, potentially leaving the navigation system more vulnerable than was the in-

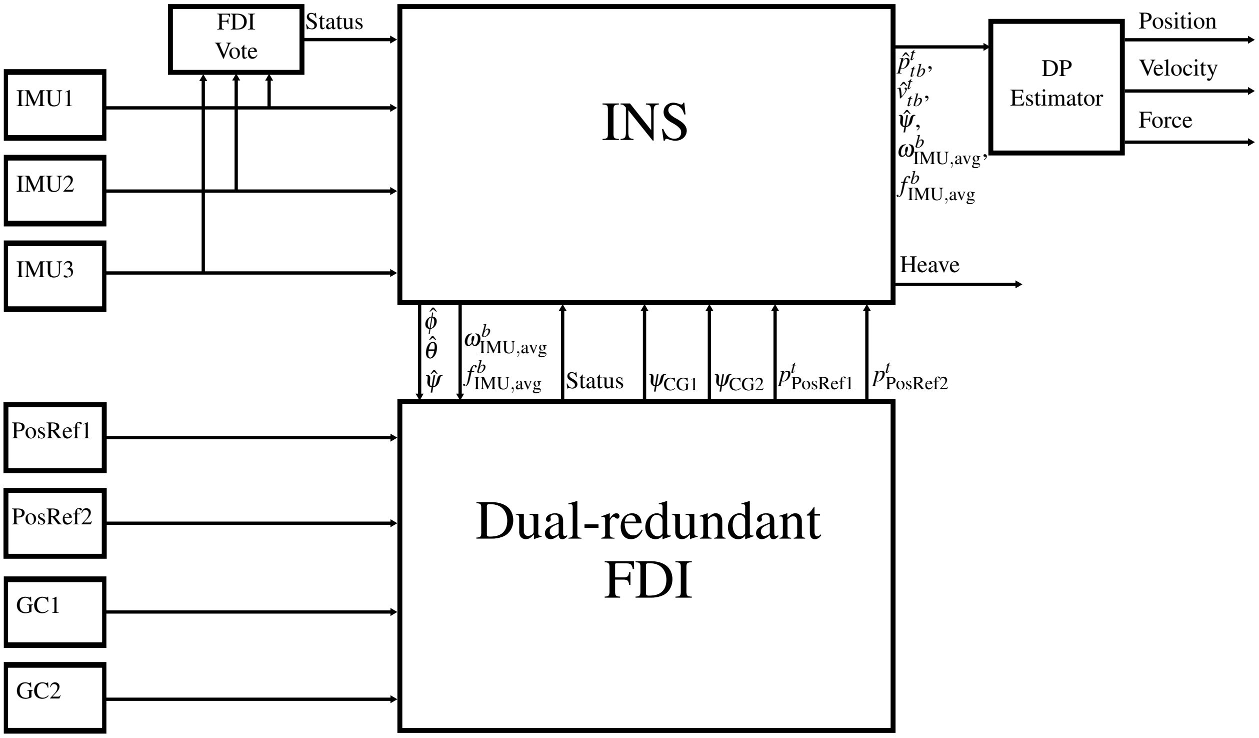

FIGURE 2. Proposed sensor structure. Detailed overview of the dual-redundant FDI is presented in Fig. 3.

tention of the triple-redundancy requirement. This is where an INS could be useful, providing position information that is independent from the position reference systems for shorter periods of time, and even from any external factors like satellites for GNSS and seabed transponders for HPR. The INS's outputs are not dependent of any medium, thus they are not susceptible to e.g. atmospheric disturbances or thruster induced acoustic noise.

Usage of INS in a DP context is not new. As several papers [14–19] discuss possible usage of INS in DP for enhancing position reference systems by filtering noise, increasing update rates, removing outliers, and providing position through dead reckoning (DR) during PosRef outages. While testifying the great effects and upsides the deployment of an INS may have, these references primarily suggest using one or two IMUs per position reference system for performance, and not fully integrate a redundant IMU solution in the DP system. [10] and [20] demonstrated the potential for using IMUs as a mean for fault detection and isolation in triple and dual position reference systems, and [21] for fault detection in the case of having a single position reference. Granted, INS based on MEMS might not be satisfactory as a separate position reference, as in the purported purpose of such systems. An unaided MEMS INS tends to drift quite a lot after a while, staying within 5 meters in 1 minute [9], but for fault-tolerance usage, w.r.t. PosRef fault detection, this might still be acceptable performance-wise. For PosRef errors that develop slower than this ($\sim$ 10 cm per second) other information might be necessary for FDI. However, in such situations, the DP operator also have more time to make a decision regarding the ongoing DP operation. Using the zero velocity update (ZUPT) measurement correction applied in [21], could improve cited results, but that remains to be investigated in full scale testing. With the help of a fiber optic gyro (FOG) or ring laser gyro (RLG) angular rate sensors, such a system may fare even better. In [16], an unaided INS was demonstrated to stay within GPS accuracy for over 2.5 minutes. Another option is to use tightly coupled integration of GNSS/HPR and IMU such that integrity monitoring of each of the individually measured (pseudo)ranges, from the respective satellites/transponders to the receiver/transducer on vessel, can be carried out. This might improve FDI in the event of slowly evolving PosRef errors or faults since fault detection can be carried out on the individual pseudorange measurements for either the GNSS or the HPR system [7, Ch. 17], exploiting the INS's capability to predict position between PosRef measurement samples. By having access to the INS one could also consider to reduce the output measurements frequency of the PosRef such that nominal noise of such systems (GNSS/HPR) will be less time-correlated, thus potentially easing the fault detection properties of the integrated navigation system.

For gyrocompasses, the concern of non-independence does not carry the same burden, as one gyrocompass is inherently in-

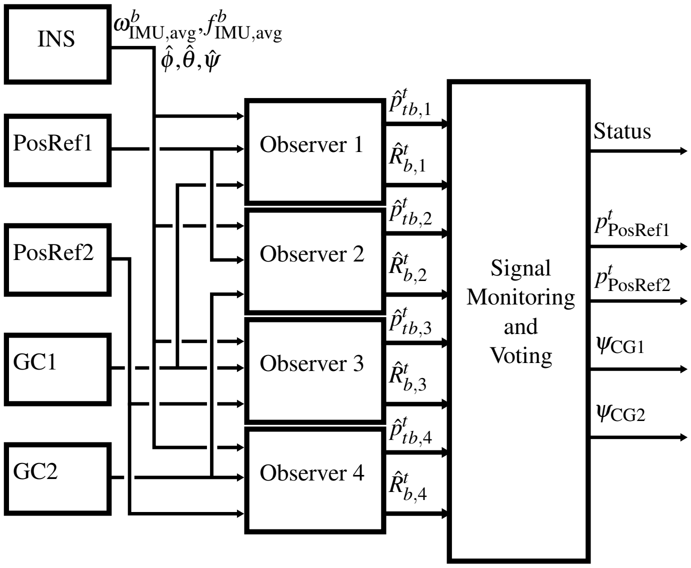

FIGURE 3. Dual-redundant FDI concept using observers and signal processing based on observer-innovation monitoring.

dependent from another. The argument for reducing the number of these vessel sensors rather comes down to cost and performance. Compared to even the highest quality MEMS angular rate sensor available for purchase, a gyrocompass is quite expensive. Addtionally, in situations where the vessel is subject to relatively high-dynamic yaw rates, the traditional gyrocompass, atleast the mechanical ones, might lag behind the output of a MEMS-based INS. In [9], a MEMS-based INS running unaided from gyrocompasses, stayed within one degree for an hour on average over 12 runs compared to the reference. [20, 22] investigates using IMUs for FDI in gyrocompasses, discovering that this is easier than for position because there is only one integrator between the IMU measurement (angular rate) and state (heading), as opposed to two integrators for position (from acceleration to position). For the reasons above, one could easily imagine replacing a gyrocompass with a triple-redundant MEMS IMUs configuration, as the latter is also useful in other parts of the DP system. State of the art within MEMS angular rate sensors also allows for a single IMU to be utilized a heading reference for a limited amount of time if both gyrocompasses are unavailable.

A potential strategy to ensure sufficient FDI with dual PosRefs and heading references is illustrated in Fig. 3. Here, additional observers are introduced, one for every combination of PosRef, gyrocompass and averaged IMU measurements. A fault detection algorithm is employed, monitoring the residuals for each combination of observers and sensors enabling both fault isolation and potential identification. Thus by increasing the number of observers one may avoid a third reference system.

Using IMUs instead of Wind Sensors in Force and Moment Calculations

A ship can be exposed to environmental forces and moments as indicated in (2)–(3). The forces and moments may stem from current, waves, wind and is in some cases ice loads. Wind sensors, measuring wind speeds and directions, together with using models including wind coefficients related to the wind projection area, are utilized in order to calculate the wind forces and moments. These calculations are prone to errors in measurement of wind speed, direction and projection area. The wind is not necessarily uniform such that the location of the wind sensors of the ship can also influence these calculations (sheltering effects due to sensor location, structure-induced turbulence etc.), [3]. In addition, the wind force also must be lowpass filtered such that force from wind gusts is prevented to enter the control loop, [4].

Reliable environmental force estimates can be obtained by exploiting the IMU measurements, since the inertial sensors measure vessel motions induced by the environment and the control system. Reliable accelerations and angular velocity responses, due to wind (or other environmental forces), are obtained regardless of wind type and wind sensor location with the redundant IMU configuration presented above. Based on this and the other estimates from the INS, the unknown aggregated environmental forces can be obtained by augmenting the vessel model (2)–(3), with the non-physical quantity $b \in \mathbb{R}^3$. This quantity represents unmodeled forces and moments, in our case forces and moments due to wind, waves, current and possibly ice, without using the wind sensor, even for wind loads with moderate and faster dynamics. The resulting model can take the form:

$$\dot{\eta} = R(\psi)\nu, \tag{10}$$

$$\dot{\nu} = M^{-1}\left(-D\nu + b + \tau_{\text{DP}},\right) \tag{11}$$

$$\dot{b} = -T^{-1}b. \tag{12}$$

The matrix $T \in \mathbb{R}^{3\times3}$ can be chosen as a diagonal matrix consisting of the axes' time constants, which are considered as tuning variables. For control purposes one can design an estimator or observer for the vessel model (10)–(12), to estimate b using the measurements

$$y = \begin{pmatrix} p^n_{\text{INS},x} \\ p^n_{\text{INS},y} \\ \psi_{\text{INS}} \\ v^n_{\text{INS},x} \\ v^n_{\text{INS},y} \\ \omega^b_{\text{IMU,avg},z} \\ f^b_{\text{IMU,avg},x} \\ f^b_{\text{IMU,avg},y} \end{pmatrix}, \tag{13}$$

obtained from the INS and the averaged redundant inertial sensors. By putting the system on a general dynamic form

$$\dot{x} = f(x,u), \tag{14}$$

$$y = h(x,u), \tag{15}$$

where $x = (\eta;\nu;b)$ and $u = \tau_{\mathrm{DP}}$ and

$$h(x,u) = \begin{pmatrix} \eta \\ R_b^t(\psi)\nu \\ C_{\mathrm{acc}}M^{-1}\left(-D\nu + b + \tau_{\mathrm{DP}}\right) \end{pmatrix}, C_{\mathrm{acc}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}. \tag{16}$$

The residual generalized force b is easily estimated with e.g. an extended Kalman filter without utilizing the wind sensors since b is the only state that is not measured. In addition, the two upper components of the left-hand side of (11) is measured by the weighted accelerometer measurements. This facilitates a highly responsive estimate of b. Another example of such strategies centered towards DP in managed ice is [23]. Since accelerometer measurements are available, acceleration feedback in harsh weather conditions is also possible [24].

DISCUSSIONS

Cost vs. Robustness

It can be argued that dual-redundant PosRefs and gyrocompasses are less robust than the triple-redundant alternatives. Cost-wise dual-redundancy is favorable especially since both the wind sensors and VRU can be replaced with IMUs. Also saving one PosRef and gyrocompass contributes to reduced cost. In order to increase reliability further, one can spend money on more modern gyrocompass products, based on FOG, hemispherical resonator gyro (HRG) or RLG technology, [25], instead of traditional mechanical gyrocompasses in need more frequent maintenance. In a life-cycle perspective modern gyrocompasses may be cost-effective while being more reliable than traditional mechanical products.

The case was made earlier that common mode failures reduce the benefits of having two references of the same type. Regarding GNSS however, having two antennas and systems on board is still beneficial, as a separate heading reference could be obtained for free from the vector between them if the GNSS antennas are located sufficiently apart from each other, [26,27]. Because of physical separation principles, partly due to class A.60 division requirements, and partly to protect one self from GNSS shadowing, one should in any case place one system at a distance from the other.

The economical argument may also be used against dual redundancy. Triple redundancy may facilitate increased up time in the event of a failed sensor resulting in that ongoing operations can be continued until a replacement unit can be acquired.

Testing of DP system with proposed structure

Testing of DP systems is currently carried out with Failure Mode and Effects Analysis (FMEA) [28], a qualitative methodology for systemically analyzing reliability and redundancy by investigating each possible failure mode, followed by sea-trials in which certain aspects of the FMEA tests are verified. Within today's DP system architecture, FMEA is an effective tool to verify how sensor errors and faults propagate, and if fault barriers are functioning properly, but it is not without its weaknesses [29]. While DP FMEA is geared towards hardware, components and tangible systems, a more recent advancement in testing is hardware-in-the-loop (HIL) testing [30] where DP control computers are verified in a simulation environment. In this regime, it is possible to scrutinize the software of control systems not only as a single failed/not failed component, but also how they respond to different inputs, possibly leading the system to danger later on. HIL is receiving more and more attention, where [31] presents an optional enhanced reliability classification notation based on this DP system testing framework. [32] goes even further, beyond the realm of software and hardware, including human operators and organizations together with traditional components in a system-theoretic process analysis (STPA) scheme. [32] argues that the current focus on redundancy and component failure is too narrow, and that a broader strategy such as STPA could be applied to complement current testing programs.

With a new system- and risk-based approach for designing DP control systems, and perhaps even with current systems, more sophisticated testing beyond todays FMEA should be considered. Because of ever more sophisticated software and hardware arrangements, sensor faults and failures are not guaranteed to propagate predictably, but ultimately depends on a system that is more than the sum of its parts.

In case of loss of all PosRefs: Vessel-model-based Dead Reckoning (DR)

Results have shown that the position estimates of MEMS-bases INS drift fast in the event of loss of aiding, [9,12]. Therefore, in the event of loss of all PosRefs, usage of vessel-model-based DR using the DP estimator is advised since this has better natural stability properties due to the damping term, $-D\nu$, in contrast to the kinematic model of (7)–(8), which is utilized by the INS, based on pure integration. The DR performance of the model-based DR may also be improved by still utilizing both the averaged accelerometer and rate gyro measurements, in addition to, the heading measurements from the gyrocompass in the event of PosRef loss.

CONCLUDING REMARKS

We have presented a new structure for dynamic positioning vessel sensors and position reference systems. The case was made that much of current DP redundancy requirement may not improve the safety of operation as intended. Employing low-cost triple-redundant IMUs, we described many advantages that follow from using such technology: First, a vertical reference unit/vertical reference sensor solution inherently follows from the inclusion of IMUs. Second, fault-tolerance is improved, in some cases, because of independent position and heading information inferred by the inertial navigation system. Third, the wind sensor can be expelled from DP control, by measuring environmental forces directly with the IMUs, instead of through uncertain wind measurements and models.

A dual-redundancy in both gyrocompasses and position references was proposed. For gyrocompasses, we argued that two sensors for redundancy are enough, and that fault detection and isolation could be carried with the help of MEMS IMUs. For position reference, two GNSSs and an independent system were recommended, as in deep water operation generally only two types of systems are available (GNSS and HPR). In addition, two onboard GNSSs, with a sufficient baseline between them, would enable a satellite-based heading reference. In case of loss of both position reference systems, we suggested falling back on a vessel-model-based estimator. Some faults could be detected and isolated by MEMS IMUs, but for slowly emerging faults more information is need, for instance from integrity monitoring of the position reference system through tight integration with an IMU.

We noted that new methods for testing beyond FMEA should be applied when moving towards risk- and system-based design, but remarked that new methods are already being investigated and to some extent applied.

All in all, the inclusion of MEMS IMUs is arguably profitable. With low cost, but high value, both performance and fault-tolerance is potentially increased.

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