Observer and IMU-based Detection and Isolation of Faults in Position Reference Systems and Gyrocompasses with Dual Redundancy in Dynamic Positioning

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***Abstract*— Faults in position reference systems and vessel sensors pose a serious hazard during dynamic positioning, and vessel drive-offs because of erroneous data may have dire consequences. The classification society standards require triple redundancy in heading and position reference systems, but common mode failures and operational limitations could put the safety promised by the redundancy at risk. In this paper we present a way to detect and isolate faults in the aforementioned systems, using nonlinear observers and inertial measurement units (IMUs). Employing IMU acceleration and gyro data in an integration filter, and comparing estimation error outputs from multiple observers in parallel proves to be a viable method for fault detection and isolation. This exploits the possibility of using IMUs as another, independent position reference system or sensor on board a vessel.**

I. Introduction

For some marine vessel operations, in particular in dynamic positioning (DP) Classes 2 and 3, the requirements are that the vessel must have three independent position reference (posref) systems and triple redundancy in vessel sensors ([1],[2],[3]). At open sea, the most common posref systems for DP include hydro-acoustic systems, taut wire and global navigation satellite systems (GNSS), such as GPS, GLONASS and Galileo. Examples of vessel sensors are gyrocompasses and vertical reference units. While these redundancy requisites are not unreasonable in themselves, there are some challenges associated with their real-life realization.

First, satisfying the "independent" condition for the posref systems may not be trivial. Common for these systems is that they often require an external aid or reference, in the form of transponders (hydro-acoustic) or clump weights (taut wire) on the sea bed, or satellites in space (GNSS). It is not difficult to imagine scenarios where one of them are unusable. For the taut wire, water depth is a restriction, leaving only the hydro-acoustic and GNSS as viable options in deep waters. Vessel movement away from seabed equipment is a limiting factor for the hydro-acoustic system, but for DP operations staying in close proximity to the transponder is usually not a problem, since it it inherently part of the goal. With one of the posref choices out of the question, one might have to resort to ensuring redundancy by adding another posref system of the same type, e.g. ending up with a combination of two GNSS and one hydro-acoustic system. However, common mode failures put the safety promised by the redundancy at risk. In an incident study [4] cited by [5], *"six incidents are classified as drive-off, while five of these six incidents were initiated due to erroneous position data from DGPSs"*.

In addition to the redundancy issue, there is the inevitable question of cost. Adding more equipment comes at a monetary price, and since adding more systems of the same type does not necessarily enhance performance, the cost becomes superfluous. It is therefore desirable to enhance redundancy, safety and perhaps performance by adding another set of sensors that is not in the requirements today and not typically used in DP applications: the low-cost micro-electro mechanical systems (MEMS) based inertial measurement unit (IMU).

A. Inertial Measurement Units and DP

IMUs are as mentioned not in widespread use in DP systems today. While the idea of combining IMUs with a posref system such as hydro-acoustic ([6],[7]) and GNSS ([8],[9]) is not new, most of the literature focus their efforts on combining inertial sensors with a single posref system. The concept of using the IMU as a part of the redundancy scheme has been thought of ([10],[11]), but has not caught the wide eye of attention from the industry as of yet.

The limited interest in the industry so far could possibly stem from the absence of IMUs with justifiable cost vs. performance ratio, but the development of ever better performing, low-cost, MEMS-based inertial sensors, may eventually spark some enthusiasm, and this provides motivation for the following ideas.

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B. Main results

In this paper a nonlinear observer is employed, receiving input from two position reference systems, two gyrocompasses and one "reliable" IMU, the latter providing linear accelerations and angular velocities. A reliable IMU can for instance be implemented by making use of triple redundancy and voting, but it is outside the scope of this article to discuss its realization. To simplify the analysis and proof of concept further, the IMU is thought to be pre-calibrated for bias. The analysis looks at:

- observer stability
- observer measurement error with respect to faults in posref and gyrocompass
- observer tuning parameters effect on sensitivity to faults

Lyapunov analysis is employed in order to prove uniform global exponential stability (UGES) of the nonlinear observer, and it is shown to be capable of both detection and isolation of faults.

C. Organization of the paper

In Section II the system kinematics, the observer dynamics and error dynamics of the observer are derived, together with the stability analysis of the latter. In Section III simulations are carried out in order to verify the capabilities of the observer.

II. Observer for fault detection and isolation

A. The concept

The idea is to use four identical nonlinear observers, where all of them have input from the IMU, but each one only has correction from one of the four possible combinations of the two posref systems and two gyrocompasses (see Fig. 1). The observers are integration filters with no model of the vessel itself, only the kinematic relationship between heading, acceleration, velocity and position.

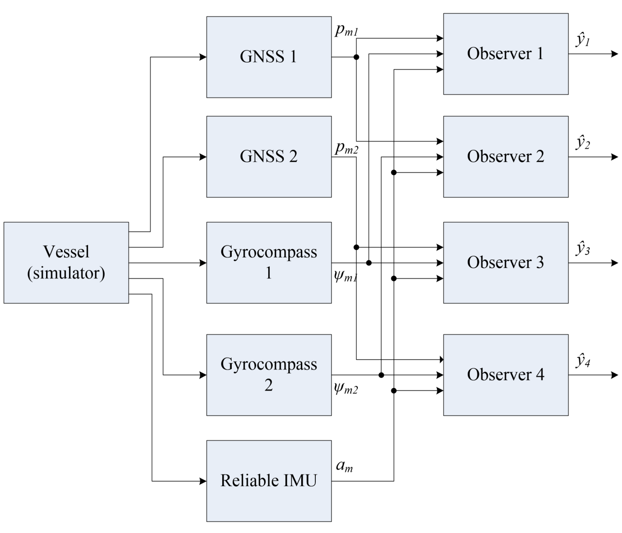

Fig. 1. Four observers in parallel.

B. Observer equations

The observer equations are based on the *"Integration Filter for Position and Linear Velocity"* found in [12], with the following adaptations and assumptions:

- Heading has been added as an estimate of the observer, instead of being considered a time-varying input, making it a 4-DOF observer.
- Attitude estimation is limited to heading only, roll and pitch are assumed to be measured.
- Earth rotation is neglected and the North-East-Down frame is assumed to be the inertial reference.
- Disturbances are assumed on the position and heading measurements.
- IMU and gyro biases are neglected, i.e. biases are assumed to be accounted for in calibration.

For simplicity, all measuring equipment are assumed to be right next to each other, in the point o_m to avoid dealing with lever arms between them.

1) Notation: For clarity and to avoid confusion, the same notation as in [12] is used:

- $\{n\}$ - North-East-Down reference frame, earth fixed tangential plane
- $\{b\}$ - body-fixed reference frame
- $\mathbf{p}^n_{m/n}$ - position of the point o_m with respect to $\{n\}$ expressed in $\{n\}$
- $\mathbf{v}^n_{m/n}$ - linear velocity of the point o_m with respect to $\{n\}$ expressed in $\{n\}$
- $\mathbf{a}^b_{imu}$ - linear acceleration measurement in the body/vessel frame $\{b\}$
- ϕ - roll, angle between between $\{b\}$ and $\{n\}$
- θ - pitch, angle between between $\{b\}$ and $\{n\}$
- ψ - heading, angle between between $\{b\}$ and $\{n\}$
- $\mathbf{\Theta}_{nb}$ - attitude, column vector with the three Euler angles
- ω_y - angular velocity about the y-axis in $\{b\}$
- ω_z - angular velocity about the z-axis in $\{b\}$
- $\mathbf{R}_z(\psi)$, $\mathbf{R}_y(\theta)$ and $\mathbf{R}_x(\phi)$ - the principal rotation matrices around the respective axes, whose products $\mathbf{R}^n_b = \mathbf{R}_z(\psi)\mathbf{R}_y(\theta)\mathbf{R}_x(\phi)$ and $\mathbf{R}^b_n = \mathbf{R}^\top_x(\phi)\mathbf{R}^\top_y(\theta)\mathbf{R}^\top_z(\psi)$ are the rotation matrices to $\{n\}$ from $\{b\}$ and vice versa, respectively
- $\mathbf{g}^n$ - gravity vector in $\{n\}$

The dynamics of our system can be described as follows:

$$\dot{\mathbf{p}}^n_{m/n} = \mathbf{v}^n_{m/n} \tag{1a}$$

$$\dot{\mathbf{v}}^n_{m/n} = \mathbf{R}^n_b(\mathbf{\Theta}_{nb})\mathbf{a}^b + \mathbf{g}^n \tag{1b}$$

$$\dot{\psi} = \omega_y \frac{\sin(\phi)}{\cos(\theta)} + \omega_z \frac{\cos(\phi)}{\cos(\theta)} \tag{1c}$$

$$\mathbf{y}_1 = \mathbf{p}^n_{m/n} + \mathbf{d}_p \tag{1d}$$

$$y_2 = \psi + d_\psi \tag{1e}$$

where $\mathbf{d_p}$ and d_ψ are disturbances or measurement faults on the position and heading, respectively. The disturbances will change according to various faults that might occur in the measuring equipment.

Copying the dynamics, and using $\mathbf{a}^b_{imu}$, θ, ϕ, $\omega_{y,imu}$ and $\omega_{z,imu}$ as measurements, we propose the following observer:

$$\dot{\hat{\mathbf{p}}}^n_{m/n} = \hat{\mathbf{v}}^n_{m/n} + \mathbf{K}_1\tilde{\mathbf{y}}_1 \tag{2a}$$

$$\dot{\hat{\mathbf{v}}}^n_{m/n} = \mathbf{R}_z(\hat{\psi})\mathbf{R}_y(\theta)\mathbf{R}_x(\phi)\mathbf{a}^b_{imu} + \mathbf{g}^n + \mathbf{K}_2\tilde{\mathbf{y}}_1 \tag{2b}$$

$$\dot{\hat{\psi}} = \omega_{y,imu}\frac{\sin(\phi)}{\cos(\theta)} + \omega_{z,imu}\frac{\cos(\phi)}{\cos(\theta)} + k_3\tilde{y}_2 \tag{2c}$$

$$, \cos(\theta) \neq 0$$

$$\hat{\mathbf{y}}_1 = \hat{\mathbf{p}}^n_{m/n} \tag{2d}$$

$$\hat{y}_2 = \hat{\psi} \tag{2e}$$

where $\tilde{\mathbf{y}}_1 = \mathbf{y}_1 - \hat{\mathbf{y}}_1$ and $\tilde{y}_2 = y_2 - \hat{y}_2$ are the injection terms. For ships, one can assume that θ will never be equal to $\pm 90°$, thus $\cos(\theta) \neq 0$.

C. Stability of observer

For the stability analysis the disturbances will be disregarded. How they affect the equilibrium points will be analysed in Section II-D. We assume the IMU is reliable, thus $\mathbf{a}^b = \mathbf{a}^b_{imu}$, $\omega_y = \omega_{y,imu}$ and $\omega_z = \omega_{z,imu}$.

From (1) and (2), the observer error dynamics without disturbances can be expressed as follows:

$$\dot{\tilde{\mathbf{p}}}^n_{m/n} = \tilde{\mathbf{v}}^n_{m/n} - \mathbf{K}_1\tilde{\mathbf{p}}^n_{m/n} \tag{3a}$$

$$\begin{aligned}\dot{\tilde{\mathbf{v}}}^n_{m/n} = (&\mathbf{R}_z(\psi)\mathbf{R}_y(\theta)\mathbf{R}_x(\phi) \\ &- \mathbf{R}_z(\hat{\psi})\mathbf{R}_y(\theta)\mathbf{R}_x(\phi))\mathbf{a}^b_{imu} - \mathbf{K}_2\tilde{\mathbf{p}}^n_{m/n}\end{aligned} \tag{3b}$$

$$\dot{\tilde{\psi}} = -k_3\tilde{\psi} \tag{3c}$$

where $\tilde{\mathbf{p}}^n_{m/n} = \mathbf{p}^n_{m/n} - \hat{\mathbf{p}}^n_{m/n}$, $\tilde{\mathbf{v}}^n_{m/n} = \mathbf{v}^n_{m/n} - \hat{\mathbf{v}}^n_{m/n}$ and $\tilde{\psi} = \psi - \hat{\psi}$.

Theorem 1: Suppose tuning parameters $\mathbf{K}_1$ and $\mathbf{K}_2$ are chosen such that the matrix

$$\mathbf{A} := \begin{bmatrix} -\mathbf{K}_1 & \mathbf{I} \\ -\mathbf{K}_2 & \mathbf{0} \end{bmatrix}$$

is Hurwitz and $k_3 > 0$. If all measured signals are bounded, then the origin of the observer error dynamics (3) is UGES.

Proof: Rewriting the rotation matrix term in the error dynamics (3b), using $\hat{\psi} = \psi - \tilde{\psi}$:

$$\begin{aligned}
&\mathbf{R}_z(\psi)\mathbf{R}_y(\theta)\mathbf{R}_x(\phi) - \mathbf{R}_z(\hat{\psi})\mathbf{R}_y(\theta)\mathbf{R}_x(\phi) \\
&= (\mathbf{R}_z(\psi) - \mathbf{R}_z(\hat{\psi}))\mathbf{R}_y(\theta)\mathbf{R}_x(\phi) \\
&= (\mathbf{R}_z(\psi) - \mathbf{R}_z(\psi - \tilde{\psi}))\mathbf{R}_y(\theta)\mathbf{R}_x(\phi) \\
&= (\mathbf{R}_z(\psi) - \mathbf{R}_z(\psi)\mathbf{R}_z(-\tilde{\psi}))\mathbf{R}_y(\theta)\mathbf{R}_x(\phi) \\
&= (\mathbf{R}_z(\psi) - \mathbf{R}_z(\psi)\mathbf{R}_z^\top(\tilde{\psi}))\mathbf{R}_y(\theta)\mathbf{R}_x(\phi) \\
&= \mathbf{R}_z(\psi)(\mathbf{I} - \mathbf{R}_z^\top(\tilde{\psi}))\mathbf{R}_y(\theta)\mathbf{R}_x(\phi) \\
&:= \bar{\mathbf{R}}(t, \tilde{\psi})
\end{aligned}$$

Using $\mathbf{A}$ as defined in the theorem, implies that the error dynamics can be put in the following form:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \begin{bmatrix} \mathbf{0} \\ \bar{\mathbf{R}}(t, \tilde{\psi}) \end{bmatrix} \mathbf{a}^b_{imu} \tag{4a}$$

$$\dot{\tilde{\psi}} = -k_3\tilde{\psi} \tag{4b}$$

where $\mathbf{x} = [\tilde{\mathbf{p}}^n_{m/n} \; \tilde{\mathbf{v}}^n_{m/n}]^\top$.

Consider the following Lyapunov function:

$$V(\mathbf{x}, \tilde{\psi}) = \mathbf{x}^\top\mathbf{P}\mathbf{x} + \frac{1}{2}p_2\tilde{\psi}^2 \tag{5}$$

where $\mathbf{P}$ is the positive definite solution of the Lyapunov equation $\mathbf{P}\mathbf{A} + \mathbf{A}^\top\mathbf{P} = -\mathbf{I}$ and p_2 is a positive constant. Taking the time derivative of V, we get

$$\begin{aligned}
\dot{V} &= -\mathbf{x}^\top\mathbf{x} + 2\mathbf{x}^\top\mathbf{P}\begin{bmatrix} \mathbf{0} \\ \bar{\mathbf{R}}(t, \tilde{\psi}) \end{bmatrix}\mathbf{a}^b_{imu} - p_2k_3\tilde{\psi}^2 \\
&\leq -||\mathbf{x}||_2^2 + 2p_1||\mathbf{x}||_2||\bar{\mathbf{R}}(t, \tilde{\psi})||_2 a - p_2k_3\tilde{\psi}^2
\end{aligned}$$

where $p_1 = \lambda_{max}(\mathbf{P})$ (the largest eigenvalue of $\mathbf{P}$) and $a = \max(||\mathbf{a}^b_{imu}||_2)$ [1]. Since the norm of a rotation matrix equals 1, from the definition of $\bar{\mathbf{R}}(t, \tilde{\psi})$ we get that $||\bar{\mathbf{R}}(t, \tilde{\psi})||_2$ is equal to $||\mathbf{I} - \mathbf{R}_z^\top(\tilde{\psi})||_2$. Taking the norm, and employing some trigonometric identities, the latter can be proven to be equal to $|2\sin(\frac{\tilde{\psi}}{2})|$, which is bounded by $|\tilde{\psi}|$. Then

$$\dot{V} \leq ||\mathbf{x}||_2^2 + 2p_1||\mathbf{x}||_2|\tilde{\psi}|a - p_2k_3\tilde{\psi}^2 \tag{6}$$

Introducing a new variable $\mathbf{z} = [||\mathbf{x}||_2 \; |\tilde{\psi}|]^\top$, we see that

$$\dot{V} \leq -\mathbf{z}^\top\mathbf{\Gamma}\mathbf{z} \tag{7}$$

where

$$\mathbf{\Gamma} = \begin{bmatrix} 1 & -p_1a \\ -p_1a & p_2k_3 \end{bmatrix} \tag{8}$$

In order for $\mathbf{\Gamma}$ to be positive definite, we need to choose $p_2k_3 > p_1^2a^2$, or

$$p_2 > \frac{p_1^2a^2}{k_3} \tag{9}$$

Here p_2 can be chosen freely (larger than 0) while satisfying the inequality. Finally, we get

$$\begin{gathered}
c_1||z||_2^2 \leq V(\mathbf{z}) \leq c_2||z||_2^2 \\
\dot{V} \leq -c_3||z||_2^2
\end{gathered}$$

where $c_1 = \min(\lambda_{min}(\mathbf{P}), \frac{1}{2}p_2)$, $c_2 = \max(\lambda_{max}(\mathbf{P}), \frac{1}{2}p_2)$ and $c_3 = \lambda_{min}(\mathbf{\Gamma})$. According to Theorem 4.10 of [14], this proves that the origin of the error dynamics (3) is UGES. ■

The gains $\mathbf{K}_1$ and $\mathbf{K}_2$ must be chosen such that $\mathbf{A}$ is Hurwitz. Since the position-velocity dynamics (1a), (1b) and (1d) is observable, with

$$\mathbf{A}_{dyn} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}, \; \mathbf{C}_{dyn} = \begin{bmatrix} \mathbf{I} & \mathbf{0} \end{bmatrix} \tag{10}$$

the eigenvalues of the matrix $\mathbf{A} = (\mathbf{A}_{dyn} - \mathbf{K}\mathbf{C}_{dyn})$, where $\mathbf{K} = [\mathbf{K}_1 \; \mathbf{K}_2]^\top$, can be assigned arbitrarily ([13]). The conditions on $\mathbf{K}_1$ and $\mathbf{K}_2$ are for example satisfied by diagonal matrices with arbitrary positive elements on the diagonal.

[1] Representing a measurement of a physical process, it can be assumed that $||\mathbf{a}^b_{imu}|| \leq a_{max}$.

D. Sensor faults vs. equilibrium points

To establish the relationship between faults, observer gains and equilibrium points, the faults are included in the error dynamics to find the steady state solutions ($\dot{\tilde{\mathbf{p}}}^n_{m/n} = \dot{\tilde{\mathbf{v}}}^n_{m/n} = \mathbf{0}, \dot{\tilde{\psi}} = 0$). The motivation for doing so is to obtain clue as to what states are affected by what faults. This knowledge will help in the comparative analysis of the output of the four observers in parallel. Assume without loss of generality that $\mathbf{K}_2$ is non-singular, and consider the following:

$$\begin{aligned} \tilde{\mathbf{p}}^{*n}_{m/n} &= \mathbf{K}_2^{-1}(\mathbf{R}^n_b(\mathbf{\Theta}_{nb}) \\ &\quad - \mathbf{R}_z(\psi - d_\psi)\mathbf{R}_y(\theta)\mathbf{R}_x(\phi))\mathbf{a}^b_{imu} - \mathbf{d}_p \quad (11a) \\ \tilde{\mathbf{v}}^{*n}_{m/n} &= \mathbf{K}_1\mathbf{K}_2^{-1}(\mathbf{R}^n_b(\mathbf{\Theta}_{nb}) \\ &\quad - \mathbf{R}_z(\psi - d_\psi)\mathbf{R}_y(\theta)\mathbf{R}_x(\phi))\mathbf{a}^b_{imu} \quad (11b) \\ \tilde{\psi}^* &= d_\psi \quad (11c) \end{aligned}$$

The solutions of (11a)-(11c) tell us that static faults d_ψ in ψ-measurement can propagate to all states, but for linear velocity and position only when the vessel is accelerating. The position measurement faults d_p on the other hand will only influence the position estimate error equilibrium itself. As we have one observer for every combination of gyrocompass and position reference system, detection of faults will straightforward. However, isolation of the faulty measurement is more challenging.

Recognizing that the occurrence of faults will lead to transients in the measurement errors $\tilde{\mathbf{y}}_1 = \mathbf{y}_1 - \hat{\mathbf{y}}_1$ and $\tilde{y}_2 = y_2 - \hat{y}_2$, a continuous comparison between the error outputs of the four observers is in order. In the ideal situation without any measurement noise, two observers will experience transients due to the faults. This allows the fault to be uniquely isolated to the common posref/gyrocompass among the two observers.

The main objective of this observer is the detection and isolation of faults, so gains should be chosen with that in mind, while at the same time thinking about the effects of noise and other error sources. We should choose to have a not-so-aggressive feedback, to keep the transients lingering. On the other hand, setting the gains too low would hamper the estimating qualities of the observer.

Various methods for fault detection, isolation and identification can be found in for instance [15], [16] and [17], but they will not be the target of this paper.

III. Simulation

The simulations were carried out in MATLAB/Simulink R2013b using a dynamic ship simulator in full 6-DOF [12] with waves, vibration and measurement noise. All measurements were set to have a zero mean normally distributed noise, except for the posref systems who have a Gauss-Markov process, see Table I for their parameters. Only a single fault in the form of drifting on a single measurement is simulated in each case. The drifting speed is chosen to be fast enough to cause potential danger in a DP operation, but not so fast that it is obvious that a fault has occurred.

TABLE I
MEASUREMENT NOISES

Measurement	Std. dev.	Corr. time
IMU acceleration	0.002 m/s^2	-
IMU gyro	0.08 deg/s	-
Position reference system x and y	1.5 m	4 min
Position reference system z	2.5 m	4 min
Gyrocompass	0.1 deg	-

The following feedback gains were used in all simulations:

$$\mathbf{K}_1 = \begin{bmatrix} 0.05 & 0 & 0 \\ 0 & 0.05 & 0 \\ 0 & 0 & 0.05 \end{bmatrix}, \mathbf{K}_2 = \begin{bmatrix} 0.0005 & 0 & 0 \\ 0 & 0.0005 & 0 \\ 0 & 0 & 0.0005 \end{bmatrix}$$

and $k_3 = 0.1$.

A. Gyrocompass drift

For the first case, a simulation of a gyrocompass drift was simulated. The drift was set to 0.4 deg/s at $t = 50$ seconds in Gyrocompass 1 (see Fig. 1), up to a maximum fault of 20 degrees. This resulted in a noticeable transient in the heading measurement error for two of the observers, namely 1 and 3, who are receiving their input from the faulty unit. Figs. 2 and 5 show the heading and heading estimates, and heading errors, respectively. The transient is visible as long as the error keeps increasing, up until it reaches 20 degrees.

B. Position reference system drift

For the second case, a position reference system (GNSS 1 in Fig. 1) was set to drift at a rate of 0.4 m/s up to a maximum fault of 20 meters. The fault was, as before, introduced at $t = 50$ seconds. The vessel was keeping its position at the origin. The simulation results are shown in Figs. 3 to 7. The performance of the observer when it comes to estimating the position accurately is less than optimal, but our objective with this observer is solely to isolate failures. To detect that something is wrong is trivial from Figs. 3 and 4, since we have two diverging estimates. Also, from Figs. 6 and 7 showing the position measurement errors in x and y, or North and East, it is possible to isolate the faulty output visually as we did for the heading error. A significant transient occurs during the sensor drift-away.

C. Discussion

As the simulation results demonstrate, it is possible to use the estimation errors to detect and isolate faults. However, assumptions were made that the gyro and accelerometer biases were perfectly accounted for, but this is seldom the case. In addition, one could think of scenarios with smaller sensor drifts and larger measurement and process noise. In these cases it will probably be more difficult to distinguish the faults. In [15], there are methods that describe applying a filter to the measurement error, in order to generate *residuals*. These filters should be designed so that noise and other error sources are masked out from the residual.

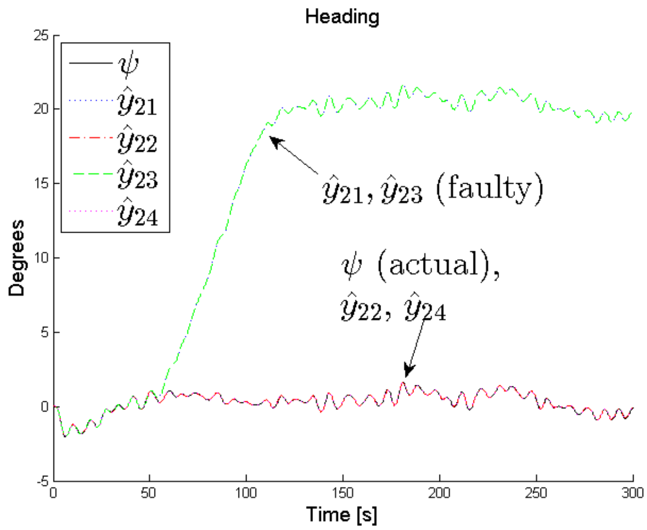

Fig. 2. Heading and heading estimates, sensor drift 1 deg/s.

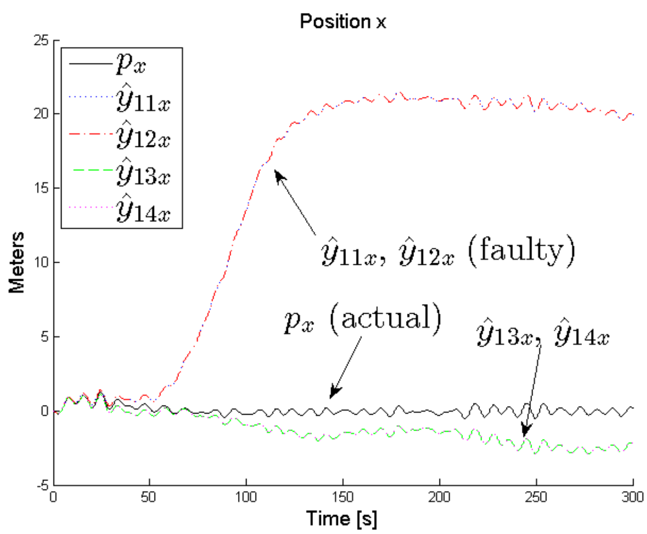

Fig. 3. North position and estimates, posref drift 0.1 m/s.

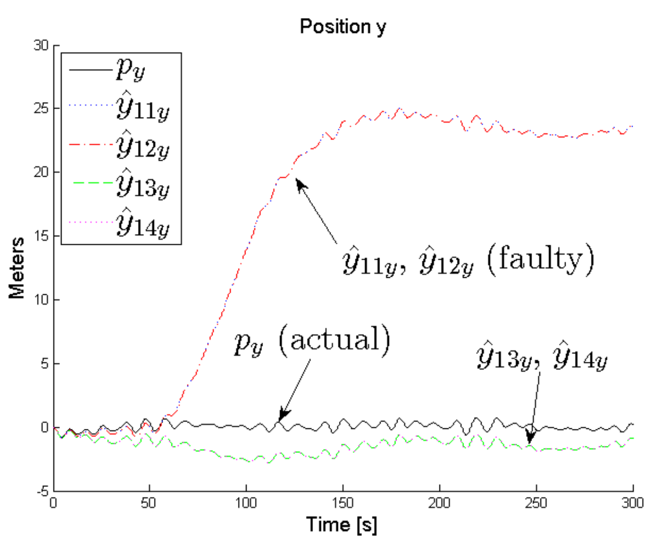

Fig. 4. East position and estimates, posref drift 0.1 m/s.

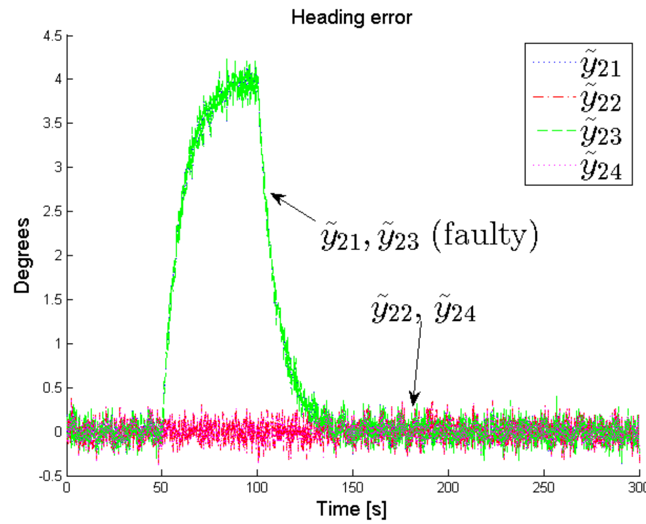

Fig. 5. Heading measurement error, sensor drift 1 deg/s.

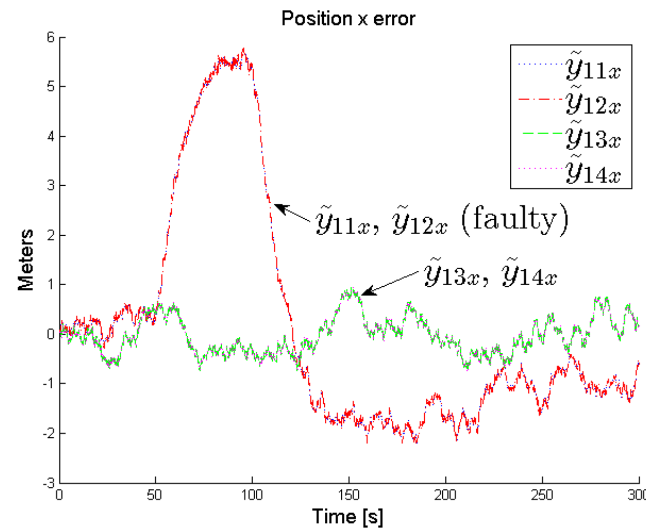

Fig. 6. North position measurement error, posref drift 0.1 m/s.

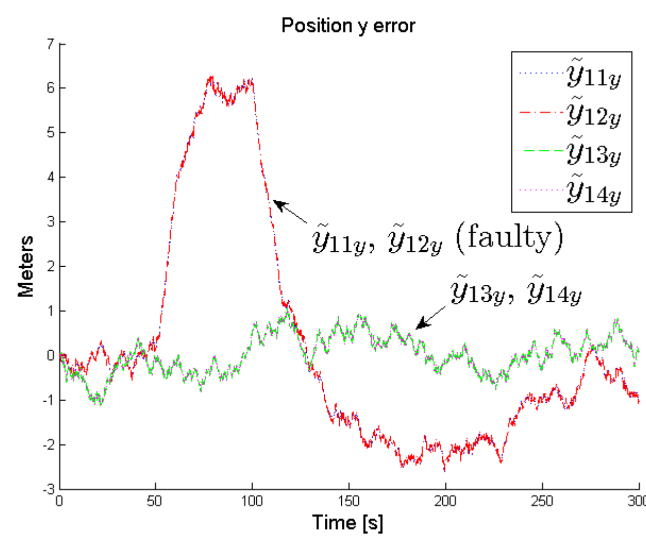

Fig. 7. East position measurement error, posref drift 0.1 m/s.

IV. Conclusion

In this paper we have presented a scheme for observer and IMU-based detection and isolation of faults. The main objective was to find out which of either two position reference systems or gyrocompasses had failed. A nonlinear observer for integration of IMU measurement was introduced, and it was proven to be uniformly globally exponentially stable. The observers were run four in parallel, representing every combination of the gyrocompasses and posrefs, and by comparing the measurement errors of each observer, we were able to isolate the source of the fault.

However, the IMU was assumed to be reliable and without bias, both for the acceleration and gyro measurement, which can hardly be said to be the case in the real world. By introducing bias, one would also need to add bias estimation, adding complexity and more sources for error in the observer. A natural suggestion for further work is thus to remove this assumption, and expand the observer accordingly.

An issue that may affect the performance of the fault detection and isolation is measurement noise. Methods for filtering the measurement noise to account for this should be investigated in the future.

Acknowledgment

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