Ship Security Relative Integrated Navigation with Injected Fault Measurement Attack and Unknown Statistical Property Noises

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Abstract: In this work, the ship relative integrated navigation approaches are studied for the navigation scenarios with the measurements disturbed by unknown statistical property noises and with the injected fault measurement attacks. On the basis of the limited energy property of system noises, the navigation states are estimated by the local finite horizon $\mathcal{H}_\infty$ filter to satisfy the performance index function. Then, the local estimates are fused in the relative integrated navigation system with the weight fusion parameters obtained by using the local estimate error measurements. Further, the injected fault measurement attacks are considered in the relative integrated navigation systems. Due to the system noises and the measurement noises having unknown statistical property, the classical Chi-square test can hardly be utilized to detect the injected fault measurements. Therefore, a secure relative integrated navigation method is proposed with a distance-based clustering detector. The final simulation results illustrate the effectiveness of the proposed relative integrated navigation approach and the proposed secure relative integrated navigation approach.

Keywords: injected fault measurement attack; relative integrated navigation; secure integrated navigation; unknown statistical noise

1. Introduction

The application of maritime communication networks brings opportunities and challenges to ship integrated navigation systems. The ship integrated navigation system can use the navigation information transmitted by the network to improve its own navigation accuracy. Meanwhile, it may be maliciously interfered by network attackers. Therefore, the research on secure integrated navigation methods is gradually becoming an important and key direction for integrated navigation research.

The integrated navigation system fuses the measurements obtained from GPS, inertial navigation system (INS), radar system and other navigation devices to provide accurate and reliable navigation information and is widely used in various types of ships [1–6]. With the development of marine communications technology, the International Maritime Organization (IMO) stipulates that the automatic identification systems (AIS) should be installed on international navigation vessels of 300 gross tonnage and above, non-international vessels of 500 gross tonnage and above and all passenger ships. AIS realizes the automatic exchange of important information such as position, speed, heading, ship name, call sign, etc., between ships and shores and between ships in a certain sea area. The position information of adjacent ships can be transformed into the pseudo measurement about the target ship. This is the so-called relative navigation information [7–12], and the adjacent ships in certain sea area around the target ship are taken as the relative navigation devices. In addition to
using the navigation information from the target ship inherent navigation devices, the target ship’s relative integrated navigation system can also use the relative navigation measurements to obtain more accurate navigation information. In [7–9], the ship relative integrated navigation methods were given to fuse the navigation measurements obtained by the navigation devices owned to the target ship and relative navigation information from the adjacent ships, by using the Kalman fusion filter approach. In [10], the GPS single difference was taken to design a relative navigation method between vessels. In [11], a relative integrated navigation approach was developed to deal with the delay navigation information caused by the narrow communication bandwidth. However, it is noted that most of integrated navigation methods [1–6] and the relative integrated navigation methods above [7–11] were presented on the basis of the fusion filtering methods developed from Kalman filter, which require the system to assume that the system noise satisfies the Gaussian distribution with known mean and covariance. However, in practice, the statistical property of the navigation system noise is often difficult to accurately acquire. It is because that ships are often disturbed by wind, storm, surge, current or other sea factors [12].

It is noted that the system noise energy is usually limited in finite horizon. On this basis, the integrated navigation approach was studied with the augmented measurements including the measurements from INS and GPS in [13], by using the finite horizon $H_\infty$ filter. Further, the finite horizon $H_\infty$ central fusion method was utilized in the above integrated navigation approaches [14,15]. Obviously, the integrated navigation approaches developed from the finite horizon $H_\infty$ central fusion methods can also be improved to simultaneously deal with the measurements from the inherent navigation devices and the relative navigation measurements. Although these integrated navigation methods can improve the accuracy of ship navigation, if the measurements are attacked by hackers during communication, these integrated navigation approaches lack the necessary security detection and defense method, which will inevitably cause serious consequences.

Security is one of the most important requirements for the integrated navigation systems, which should be non-fragile to the malicious attacks. A number of results have been studied to detect, analyze and handle malicious attacks, which are mainly classified into two categories: Denial of Service (DoS) attack and deception attack [16–25]. The DoS attack is to jam the communications network to reduce the measurements received by the information processing center (IPC) [16–23]. For the relative integrated navigation systems, the results of DOS attack are usually manifested as the integrated navigation system not being able to receive several relative measurements in time. The deception attack is to modify the measurements by injecting the fault data (IFD) [24–29]. For the relative integrated navigation systems, if the fault measurements are injected and received by the integrated navigation systems, it will result into larger bias of the navigation information. If the ship is controlled based on the navigation information, it will cause more serious consequences. Therefore, the research on secure relative integrated navigation approaches is gradually becoming an important and key direction for integrated navigation research.

In this work, the secure relative integrated navigation approach is studied by using the inherent and relative measurements with unknown statistical property, which may be injected with false data during communication transmission. Firstly, a relative integrated navigation approach is presented, on the basis of the finite horizon $H_\infty$ distributed fusion filter, with the measurements disturbed by unknown statistical property noises. Further, the IFD attacks are considered in the relative integrated navigation systems. Due to the system noises and the measurement noises having unknown statistical property, the classical Chi-square test can hardly be utilized to detect the IFD [30,31]. A secure relative integrated navigation method with distance-based clustering detector is proposed. The final simulation verifies the effectiveness of the relative integrated navigation approach based on the finite horizon $H_\infty$ distributed fusion filter and the proposed secure relative integrated navigation approach.

The rest of this paper is organized as follows. Section 2 introduces the dynamic models of the target ship and the adjacent ships. The relative measurement transformation is presented in Section 3. In Section 4, the relative integrated navigation approach based on the finite horizon $H_\infty$ distributed
fusione riven for the measurements disturbed by unknown statistical property noises. The secure relative integrated navigation method is proposed in Section 5. A simulation example is provided to illustrate the effectiveness of the proposed methods in Section 6, and Section 7 concludes this work.

2. System Formulation

Consider the following linear kinematic models of a target ship and several adjacent ships in certain sea area.

\[ x_i(k + 1) = F_i(k + 1, k)x_i(k) + w_i(k), i = 1, 2, \cdots, N \]  

where \( k \) is the discrete time index, \( x_i(k) = [x_i(k), y_i(k), v_i(k), \varphi_i(k)]^T \) expresses the ship’s state vector, \( x_i(k), y_i(k), v_i(k), \varphi_i(k) \) respectively refer to the east position, the north position, the speed and the course of Ship \( i \), \( i = 1, 2, \cdots, N \) and \( N \) is the number of the ships in the sea area. \( F_i(k + 1, k) \) expresses the state transfer matrix of Ship \( i \) from \( k \) to \( k + 1 \). \( w_i(k) \) is the process noise with unknown statistical property. For easy introduction of the method designed in this paper, denote Ship 1 as the target ship, and Ship \( l \) \( (l \in \{2, \cdots, N\}) \) as its adjacent ships.

The following two kinds of navigation information are received and fused in the relative integrated navigation systems. The first one is the measurement obtained from the inherent navigation devices, such as, GPS, INS. The second one is the relative measurement obtained from the adjacent ship by using AIS and transformed by the integrated navigation system. The relative navigation measurement transformation will be given in the next section. All these measurements can be preprocessed and described as follows:

\[ y_i(k) = H_i(k)x_i(k) + v_i(k)l = 1, 2, \cdots, M(k) \]  

where \( y_i(k) \) is the (relative) navigation measurement of the \( l \)th device, \( H_i(k) \) is the measurement matrix, and \( v_i(k)l \) is the measurement noise whose statistical property is unknown. \( M(k) \) is the number of navigation measurements received by the relative integrated navigation system at \( k \).

Denote the signal of interest on the navigation of target ship as

\[ z(k) = L(k)x_1(k) \]  

Commonly, the whole navigation state vector is focused on; then, \( L(k) = I \), and \( z(k) = x_1(k) \). Only the position of target ship gets more attention if \( L(k) = \begin{bmatrix} I_{2 \times 2} & 0_{2 \times 2} \end{bmatrix} \).

With the development of marine communications technology, more and more navigation information can be obtained and used to improve the navigation accuracy of target ships. However, in the communication network of navigation information, when an injected false measurement attack occurs, it brings challenges to the secure navigation of ships. How to detect injected false measurements is the most important issue in this research. If the system noise meets the Gaussian distribution, the Chi-square test can be used to detect IFD attacks. However, the system noise statistical property of the relative integrated navigation systems studied in this paper are unknown. It is difficult to apply the attack detection methods based on statistical property. Therefore, in this paper, a secure relative integrated navigation approach will be studied to reduce the influence from the following two aspects: the system noises with unknown statistical property and the IFD attacks.

3. The Relative Measurement Transformation

By using AISs, the ships in a certain sea area automatically exchange the navigation state information, such as the position and the speed, which can be transformed as the relative navigation measurement of adjacent ships. The relative measurement transformation is introduced in this section.

As given in Figure 1, an adjacent ship \( i \) is near the target ship 1. Denote the distance and the observation angle from the target ship 1 to the adjacent ship \( i \) as \( r_{1i}(k), \theta_{1i}(k) \), which could be obtained by the radar system on the target ship. The measurements are denoted as \( \eta_{1i}(k), \eta_{2i}(k) \) in this section.
In the first or fourth quadrants, the positions of the two ships satisfy the following function.

\[
\begin{cases}
    x_i(k) = x_1(k) + r_{1,j}(k) \cos \theta_{1,j}(k) \\
    y_i(k) = y_1(k) + r_{1,j}(k) \sin \theta_{1,j}(k)
\end{cases}
\]  

\( (4) \)

While in the second or third quadrants, the positions of the two ships satisfy

\[
\begin{cases}
    x_i(k) = x_1(k) - r_{1,j}(k) \cos \theta_{1,j}(k) \\
    y_i(k) = y_1(k) - r_{1,j}(k) \sin \theta_{1,j}(k)
\end{cases}
\]  

\( (5) \)

Assume the measurement function of the radar system is given by

\[
\begin{cases}
    \eta_{1,i}(k) = r_{1,j}(k) + \tilde{\nu}_{1,i}(k) \\
    \eta_{2,i}(k) = \theta_{1,i}(k) + \tilde{\nu}_{2,i}(k)
\end{cases}
\]  

\( (6) \)

here \( \tilde{\nu}_{1,i}(k) \), \( \tilde{\nu}_{2,i}(k) \) are the corresponding measurement noises.

Let \( \hat{x}_i(k|k), \hat{y}_i(k|k) \) be the position estimate of Ship \( i \). Then the target ship obtains this estimate by its AIS and transforms it into the relative measurement as follows.

In the first or fourth quadrants,

\[
\begin{cases}
    \hat{x}_i(k|k) = x_1(k) + \eta_{1,i}(k) \cos \eta_{2,i}(k) + \tilde{\nu}_{1,x}(k) \\
    \hat{y}_i(k|k) = y_1(k) + \eta_{1,i}(k) \sin \eta_{2,i}(k) + \tilde{\nu}_{1,y}(k)
\end{cases}
\]  

\( (7) \)

In the second or third quadrants,

\[
\begin{cases}
    \hat{x}_i(k|k) = x_1(k) - \eta_{1,i}(k) \cos \eta_{2,i}(k) + \tilde{\nu}_{2,x}(k) \\
    \hat{y}_i(k|k) = y_1(k) - \eta_{1,i}(k) \sin \eta_{2,i}(k) + \tilde{\nu}_{2,y}(k)
\end{cases}
\]  

\( (8) \)

namely,

\[
y'_i(k) = H'_i(k)x_1(k) + \nu'_i(k)
\]  

\( (9) \)
where

\[
y^*_l(k) = \begin{bmatrix} \hat{x}_l(k|k) \\ \hat{y}_l(k|k) \end{bmatrix} + \begin{bmatrix} \eta_{1,l}(k) \cos \eta_{2,l}(k) \\ \eta_{1,l}(k) \sin \eta_{2,l}(k) \end{bmatrix}, \quad \text{in 1st or 4th quadrants}
\]

\[
y^*_l(k) = \begin{bmatrix} \hat{x}_l(k|k) \\ \hat{y}_l(k|k) \end{bmatrix} - \begin{bmatrix} \eta_{1,l}(k) \cos \eta_{2,l}(k) \\ \eta_{1,l}(k) \sin \eta_{2,l}(k) \end{bmatrix}, \quad \text{in 2nd or 3rd quadrants}
\]

\[
H^*_l(k) = \begin{bmatrix} I_{2 \times 2} & 0_{2 \times 2} \end{bmatrix}, \quad v^*_l(k) = \begin{bmatrix} \tilde{\nu}_{1,x}(k) \\ \tilde{\nu}_{1,y}(k) \end{bmatrix}
\]

Remark 1. The above relative measurement noises \(\tilde{\nu}_{1,x}(k), \tilde{\nu}_{1,y}(k)\) describe the model bias of the measurement functions in (7–9). Generally, the statistical attributes of the relative measurement noises are difficult to solve. In this work, the assumption that the energies of the relative measurement noise are limited is utilized to design the relative integrated navigation approaches.

4. The Finite Horizon \(H^\infty\) Distributed Fusion Filter-Based Relative Integrated Navigation

In this section, for the (relative) measurements with unknown statistical property, a finite horizon \(H^\infty\) fusion filter algorithm is presented, in the distributed fusion framework, by utilizing the property that the energies of the system noises are limited, namely, \(\sum_{k=0}^{T} (w^T_l(k)w_l(k)) < \infty\) and \(\sum_{k=0}^{T} (v^T_l(k)v_l(k)) < \infty, l = 1, 2, \ldots, M(k)\).

In the distributed framework, the measurements from the target ship inherent devices and the relative measurement from the adjacent ships in certain sea area are utilized to obtain the local estimates of the target ship navigation state focused on. Then, in the fusion center, all the local navigation state estimates of the target ship are fused to obtain the global navigation state estimate by using the estimation error measurements as the weight fusion parameters.

Firstly, the local estimate of the target ship navigation state focused on is obtained by using a finite horizon \(H^\infty\) filter with the inherent measurement or the relative measurement. Let the estimate error as \(e_z(k) := z(k) - \hat{z}(k|k)\). The performance index function of the local finite horizon \(H^\infty\) filter is given by

\[
\sup_{u \in U} \sum_{i=1}^{k} e^T_z(i)e_z(i) < \infty
\]

\[
\sum_{i=1}^{k} (v^T_l(i)v_l(i)) + \sum_{i=0}^{k-1} (w^T_l(i)w_l(i)) + (x(0) - \hat{x}_0)P^{-1}_0(x(0) - \hat{x}_0)
\]

where \(x(0)\) and \(\hat{x}_0\), respectively, are the initial state and its initial estimate of the target ship. \(\gamma\) is the performance index value. \(P_0^{-1}\) is the inverse of a given positive definite matrix, which is utilized to measure the estimate error of the initial state.

Under the above performance index, the target ship navigation state focused on can be estimated, with the (relative) measurement \(y_l(k), l = 1, 2, \ldots, M(k)\), by

\[
\hat{x}_l(k|k) = L(k)\hat{x}_{1,l}(k|k)
\]

where \(\hat{x}_{1,l}(k|k)\) expresses the estimate of \(x_1(k)\) updated with the (relative) measurement \(y_l(k)\).

\[
\hat{x}_{1,l}(k|k) = F_1(k, k-1)\hat{x}_{1,l}(k-1|k-1) + K_{1,l}(k)y_l(k) - \tilde{H}(k)F_1(k, k-1)\hat{x}_{1,l}(k-1|k-1)
\]

\[
K_{1,l}(k) = P_{1,l}(k)H^T_l(k)H_l(k)P_{1,l}(k)H^T_l(k) + I
\]

\[
P_{1,l}(k) = F_1(k, k-1)R_{1,l}(k-1)F_1^T(k, k-1) + I
\]

\[
\hat{x}_{1,l}(k|k) = F_1(k, k-1)\hat{x}_{1,l}(k-1|k-1) + K_{1,l}(k)y_l(k) - \tilde{H}(k)F_1(k, k-1)\hat{x}_{1,l}(k-1|k-1)
\]

\[
K_{1,l}(k) = P_{1,l}(k)H^T_l(k)H_l(k)P_{1,l}(k)H^T_l(k) + I
\]

\[
P_{1,l}(k) = F_1(k, k-1)R_{1,l}(k-1)F_1^T(k, k-1) + I
\]
\[ R_{1,j}(k) = P_{1,j}(k) - P_{1,j}(k) \begin{bmatrix} H_l^T(k) & L_l^T(k) \end{bmatrix} R_{e,j}^{-1}(k) \begin{bmatrix} H_l(k) \\ L_l(k) \end{bmatrix} P_{1,j}(k) \]  
(16)

\[ R_{e,j}(k) = \begin{bmatrix} I & 0 \\ 0 & -\gamma^2 I \end{bmatrix} + \begin{bmatrix} H_l(k) \\ L_l(k) \end{bmatrix} P_{1,j}(k) \begin{bmatrix} H_l^T(k) & L_l^T(k) \end{bmatrix} \]  
(17)

here, \( K_{1,j}(k) \) is the local filter gain to estimate the target ship navigation state with the \( l^{th} \) (relative) measurement. \( R_{1,j}(k) \) is utilized to measure the local estimate error.

The existing condition of the local finite horizon \( H_\infty \) filter above is

\[ P_{1,j}(k) + \begin{bmatrix} H_l(k) \\ L_l(k) \end{bmatrix} \begin{bmatrix} I & 0 \\ 0 & -\gamma^2 I \end{bmatrix} \begin{bmatrix} H_l^T(k) & L_l^T(k) \end{bmatrix} > 0 \]  
(18)

In the distributed fusion framework, the global estimate of the target ship navigation state can be further obtained by using the measurements of the local estimate errors to obtain the fusion weight parameters

\[ \hat{x}_1(k|k) = R_1(k) \sum_{i=1}^{M(\hat{c})} \left( R_{1,j}^{-1}(k) \hat{x}_{1,j}(k|k) \right) \]  
(19)

where \( R_1(k) = \left( \sum_{i=1}^{M(\hat{c})} \left( R_{1,j}^{-1}(k) \right) \right)^{-1} \).

5. The Secure Relative Integrated Navigation Method

In the last section, a finite horizon \( H_\infty \) distributed fusion filter method is presented to estimate the target ship navigation state focused on, with the (relative) measurements obtained from the target ship inherent navigation devices and the adjacent ships. However, if camouflaged fault measurements are injected in the communications network and received by the relative integrated navigation system, the navigation accuracy will be severely affected. If the target ship is further controlled in accordance with the affected navigation information, it will cause even more serious consequences. Therefore, a secure relative integrated navigation method is proposed in this section, with a distance-based network attack detector.

Because the system noises and the (relative) measurement noises have unknown statistical property, the classical Chi-square test approaches can hardly be utilized to detect the injected fault measurements (IFMs) received by the relative integrated navigation system. With the help of clustering analysis theory, a distance-based network attack detector is presented to detect the IFMs in the relative integrated navigation system. This detection method is designed with the assumption that at least one measurement from the target ship’s inherent navigation device is trustworthy and is called the secured measurement [31]. Without loss of generality, denote the secured measurement as \( y_1(k) \) and the local estimate of the target ship navigation state obtained with \( y_1(k) \) is \( \hat{x}_{1,1}(k|k) \).

The measurements from different navigation devices may be described in different forms. Therefore, we do not directly design the detector for the (relative) measurements. First, all the measurements received by the relative integrated navigation system are utilized to obtain the corresponding local estimates by using (12)–(17). Then, with the help of clustering analysis theory, a distance-based IFM detector is designed to divide these local estimates into two classes: the class containing true local estimate and the class with local estimates from IFMs. Denote C1 and C2 as two classes of the local estimates, the mean values of which are denoted as \( \hat{x}_{1}^{(\alpha)}(k|k) \), \( \alpha = 1, 2 \), in the \( i^{th} \) iterative clustering process. The iterative clustering approach is given as follows.

(1) Start with \( \hat{x}_1^{(1)}(k|k) = \hat{x}_1(k|k) \) and \( \hat{x}_1^{(2)}(k|k) = \hat{x}_{M(k)}(k|k) \).
(2) Calculate the distance between the position estimate of each local estimate \( \hat{x}_i(k|k), \ l = 1, 2, \cdots, M(k) \) and the position estimate in \( \hat{x}_i^{(a)}(k|k), a = 1, 2. \)

\[
d_i^{(a)}(k) = \sqrt{(\hat{x}_i(k|k) - \hat{x}_i^{(a)}(k|k))^2 + (\hat{y}_i(k|k) - \hat{y}_i^{(a)}(k|k))^2}
\]  

(20)

where \( \hat{x}_i(k|k), \hat{y}_i(k|k) \) and \( \hat{x}_i^{(a)}(k|k), \hat{y}_i^{(a)}(k|k) \) are respectively the estimates of the east position as well as the north position in \( \hat{x}_i(k|k) \) and \( \hat{x}_i^{(a)}(k|k) \).

(3) If \( d_i^{(1)}(k) \leq d_i^{(2)}(k), \ \hat{x}_i(k|k) \in C_1. \) Otherwise, \( \hat{x}_i(k|k) \in C_2. \)

(4) Re-calculate the mean values of C1 and C2.

\[
\begin{align*}
\hat{x}_i^{(1)}(k|k) &= \frac{\sum_{i=1}^{N} \beta_i(k) \hat{x}_i(k|k)}{\sum_{i=1}^{N} \beta_i(k)} \\
\hat{x}_i^{(2)}(k|k) &= \frac{\sum_{i=1}^{N} (1-\beta_i(k)) \hat{x}_i(k|k)}{\sum_{i=1}^{N} (1-\beta_i(k))}
\end{align*}
\]

(21)

here \( \beta_i(k) = \begin{cases} 1 & \hat{x}_i(k|k) \in C_1 \\ 0 & \hat{x}_i(k|k) \in C_2 \end{cases} \).

(5) Repeat (2)–(5) until the mean values of C1 and C2 do not change. Then, take the class including \( \hat{x}_{1,1}(k|k) \) as the class containing true local estimate, and the other one as the class with local estimates from IFMs.

(6) Denote the local estimates included in the class containing true local estimate as \( \left\{ \tilde{x}_i^*(k|k) : i = 1, 2, \cdots, \sum_{i=1}^{M(k)} \beta_i(k) \right\} \) and its corresponding estimation error measurements as \( \tilde{R}_{1,i}(k) \).

The fusion estimate and its variance are given by

\[
\begin{align*}
\tilde{R}(k|k) &= \sum_{i=1}^{M(k)} \beta_i(k) \left( R_{1,i}(k) \right)^{-1} \\
\tilde{x}(k|k) &= \tilde{R}(k|k) \sum_{i=1}^{M(k)} \beta_i(k) \left( R_{1,i}(k|k) \right)^{-1} \tilde{x}_i^*(k|k)
\end{align*}
\]

(22)

(7) The global estimate of the target ship navigation state focused on is obtained by

\[
\tilde{z}(k|k) = L(k) \tilde{x}(k|k)
\]

(23)

6. Numerical Simulation

In this simulation, a target ship is considered with constant course and constant speed, which is marked as Ship 1. There are four adjacent ships around the target ship in certain sea area, the navigation information of which are transformed as the relative navigation measurements of the target ship. The four adjacent ships are marked as Ship 2, Ship 3, Ship 4, Ship 5. The simulation parameters are given by Table 1.
In this simulation, the injected fault measurement is set as $y$ than the relative integrated navigation approach using the IFMs, as shown in Figures 3–5. The IFMs could be detected by the distance-based detector. Therefore, its navigation accuracy is better than those shown in Figure 3.

According to the a distributed fusion filter and the proposed secure relative integrated navigation approach, as shown in Figures 4 and 5. If the target ship is further controlled in navigation system of the target ship. Then, the IFMs will a 6th simulation time, the fault position of Ship 5 is injected and received by the relative integrated navigation approach based on the finite horizon $H_\infty$ and $L_2$ navigation information received by the target ship is injected with fault position after 60s are compared in this situation. They are respectively remarked as DRF and SRF in the simulation. “AEEP” means the absolute estimation error of position.

Take the target ship’s position as the target ship navigation state focused on; then, $z(k) = L(k)x(k)$, and $L(k) = \begin{bmatrix} I_{2\times2} & 0_{2\times2} \end{bmatrix}$.

In this simulation, the injected fault measurement is considered from the Ship 5. The Ship 5’s navigation information received by the target ship is injected with fault position after 60s (the 5th simulation time). In this simulation, the injected fault measurement is set as $y_5(k) = \begin{cases} y_5(k), & k < 60s \\ 1.5y_5(k) + v_f(k), & k \geq 60s \end{cases}$, where $v_f(k) \sim \mathcal{N}(0, R_f(k))$, $R_f(k) = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.1 \end{bmatrix}$. The relative integrated navigation approach based on the finite horizon $H_\infty$ distributed fusion filter and the proposed secure relative integrated navigation approach are compared in this situation. They are respectively remarked as DRF and SRF in the simulation. “AEEP” means the absolute estimation error of position.

As shown in Figures 2–5, the simulation results of the first 5 simulation times illustrate the effectiveness of the proposed relative integrated navigation approach based on the finite horizon $H_\infty$ distributed fusion filter and the proposed secure relative integrated navigation approach. Form the 6th simulation time, the fault position of Ship 5 is injected and received by the relative integrated navigation system of the target ship. Then, the IFMs will affect the navigation accuracy of the relative integrated navigation approach, as shown in Figures 4 and 5. If the target ship is further controlled in accordance with the affected navigation information, it will cause more serious consequences than those shown in Figure 3.

For the secure relative integrated navigation approach, most of the local estimates obtained with the IFMs could be detected by the distance-based detector. Therefore, its navigation accuracy is better than the relative integrated navigation approach using the IFMs, as shown in Figures 3–5.
than the relative integrated navigation approach using the IFMs, as shown in Figures 3–5.

If the target ship is further controlled in accordance with the affected navigation information, it will cause more serious consequences than the IFMs could be detected by the distance-based detector. Therefore, its navigation accuracy is better than the relative integrated navigation approach based on the finite horizon $H$.

For the secure relative integrated navigation approach, most of the local estimates obtained with distributed fusion filter and the proposed secure relative integrated navigation approach. Form the effectiveness of the proposed relative integrated navigation approach based on the finite horizon $H$.

The performance index value

$$\text{AEEP of North (n mail)} = \frac{\text{Position of North (n mail)}}{\text{Estimate-SRF}}$$

$$\text{AEEP of East (n mail)} = \frac{\text{Position of East (n mail)}}{\text{Estimate-DRF}}$$

Figure 2. The position curses of the target ship and its adjective ships.

Figure 3. The target ship position state and its estimates by the two approaches.

Figure 4. The absolute estimation error of east position.
7. Conclusions

In the relative integrated navigation systems, the measurements from the target ship inherent device and the relative measurements from the adjective ships can be fused to obtain more accurate navigation information. In this paper, two relative integrated navigation methods are proposed for the navigation scenarios with the measurements disturbed by unknown statistical property noises and with the injected fault measurement attacks. In the relative measurement transformation, it is implied that the statistical property of the relative measurement noises are difficult to obtain. Therefore, a finite horizon H∞ distributed fusion filter-based relative integrated navigation method is presented firstly. With the help of a distance-based clustering detector, this method is further developed as a secure relative integrated navigation method to deal with the navigation measurements including injected fault measurements.

The erroneous data injection considered in this paper belongs to one category. How to design a relative integrated navigation method with better security when multiple types of fault measurements are injected into the navigation network is one of the important issues in our further research.

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