

VTS-Oriented Route Deviation Monitoring for Autonomous Surface Vehicles Using Waypoint-Tracking Telemetry and Navigation Alerts

Dwi Antoro^{1*}, Nursyamsu², Dapid Rikardo³, Kusharyanto⁴, Setyawan Ajie Sukarno⁵

(Received: 7 August 2026 / Revised: 13 August 2026 / Accepted: 19 August 2026 / Available Online: 28 September 2026)

Abstract— Autonomous surface vehicles (ASVs) increasingly use waypoint-based navigation for hydrographic surveys, environmental observation, and other unmanned maritime missions. However, navigation performance is commonly presented as numerical tracking error, which provides limited information for shore-side operators when route consistency must be assessed during mission execution. The objective of this paper is to develop and evaluate a VTS-oriented route deviation monitoring method using waypoint-tracking telemetry and navigation alerts. The method uses planned waypoint coordinates, actual GPS position, heading, speed, mission status, and telemetry availability. Waypoint error, heading deviation, speed behavior, and telemetry continuity are evaluated through rule-based navigation status classification. Ten simulation trials and ten real-world waypoint missions were analyzed. The simulation trials produced a mean waypoint error of 0.49 m and a mean heading error of 4.21°, while the field trials produced 1.15 m and 10.8°, respectively. All waypoint missions were completed, although the field trials showed larger navigation variations than the simulation trials. The results demonstrate that waypoint-tracking telemetry can provide practical route-conformance information and support navigation alert generation for remote ASV supervision in restricted and coastal waters.

Keywords— Coastal waters; Mission supervision; Operational safety; Shore control center; Track conformance.

*Corresponding Author : dwiantoro.poltekbanden@gmail.com

1. INTRODUCTION

Autonomous Surface Vehicles (ASVs), also referred to as Unmanned Surface Vehicles (USVs), are increasingly used for hydrographic survey, coastal observation, environmental monitoring, and maritime surveillance. These platforms enable unmanned operation in shallow, restricted, or hazardous waters while reducing direct human exposure and operational cost [1], [2]. Their development is also supported by the growing use of unmanned platforms for marine fauna monitoring, shallow-water bathymetric mapping, and integrated coastal observation [3], [4].

The operational capability of ASVs depends on the integration of navigation sensors, onboard computing, communication links, and remote monitoring systems. Internet of Things and digital-twin-based observation studies have shown that real-time data acquisition and distributed monitoring are important for modern marine systems [5], [6]. In autonomous marine vehicles,

waypoint-based mission execution and onboard autonomy frameworks have also been widely used to support navigation, supervision, and mission management [7], [8].

Although waypoint navigation is a fundamental capability, route-following performance may still be affected by environmental disturbance, control uncertainty, and vehicle dynamics. Previous studies on station keeping and USV control have shown that wind, current, displacement uncertainty, and drag variation can influence the behavior of unmanned marine vehicles during operation [9], [10]. Experimental ASV studies have also demonstrated that platform integration and sea-trial validation are required to ensure practical autonomous performance in real operating conditions [11], [12].

From a shore-based perspective, Vessel Traffic Services (VTS) provide a useful conceptual basis for monitoring vessel movement, route behavior, and operational safety. The VTS concept emphasizes traffic observation and navigational assistance, while international discussions on Maritime Autonomous Surface Ships have highlighted the need for reliable supervision of unmanned and remotely operated vessels [13], [14]. Although small and medium ASVs may not always operate directly within formal VTS infrastructure, VTS-oriented monitoring logic can be adapted to transform waypoint-tracking telemetry into operator-oriented route deviation alerts.

Several supporting technologies have been developed for unmanned maritime operation, including IoT-based monitoring, wireless sensor networks, and real-time communication systems. Smart environment monitoring and ocean IoT studies demonstrate the importance of sensor-based data acquisition and remote supervision in marine applications [15], [16]. Wireless sensor networks

Dwi Antoro is with Departement of Nautika, Politeknik Pelayaran Banten, Tangerang, 15330, Indonesia. E-mail: dwiantoro.poltekpelbanten@gmail.com

Nursyamsu is with Departement of Nautika, Politeknik Pelayaran Banten, Tangerang, 15330, Indonesia. E-mail: nursyamsu5173@gmail.com

Dapid Rikardo is with Departement of Manajemen Transportasi Laut, Politeknik Pelayaran Banten, Tangerang, 15330, Indonesia. E-mail: capt.Davidricardo@gmail.com

Kusharyanto is with Departement of Manajemen Transportasi Laut, Politeknik Pelayaran Banten, Tangerang, 15330, Indonesia. E-mail: kusharyanto.poltekpelbanten@gmail.com

Setyawan Ajie Sukarno is with Departement of Automation Engineering, Politeknik Manufaktur Bandung, Bandung, 40135, Indonesia. E-mail: ajie@ae.polman-bandung.ac.id

and satellite-USV systems further show that communication and observation infrastructure are essential for persistent maritime data collection [17], [18]. However, communication and visualization alone do not provide route safety interpretation unless telemetry data are processed into operational indicators.

Previous studies have contributed important elements related to ASV monitoring, testing, routing, data acquisition, safety, and command systems. Modular autonomous-vehicle testing and maritime IoT detection provide useful foundations for validation workflow and radius-based supervision [19], [20]. Other studies have addressed buoy-based monitoring, real-time environmental observation, independent fail-safe modules, command and control units, autonomous waypoint navigation, multi-agent routing, and IoT-based USV monitoring, as summarized in Table 1.

A practical problem remains between autonomous waypoint execution and remote mission supervision. Navigation controllers typically report position, heading, waypoint error, and mission state, but these quantities are not directly expressed as operational route-conformance information. Consequently, an ASV may still complete its waypoint mission while experiencing increasing heading deviation, delayed progress, or degraded telemetry that is not immediately apparent from the waypoint error alone. For remote operators, the problem is therefore not only whether the vehicle reaches its target waypoint, but also whether the developing navigation condition requires additional attention or intervention.

waypoint error, heading deviation, speed behavior, mission status, and telemetry availability are combined within a hierarchical navigation-status assessment. Third, numerical navigation records are translated into operational alert information that can be interpreted during remote mission supervision. The method is evaluated using simulation and real-world waypoint missions from a catamaran-type ASV testbed.

II. METHOD

A. Research Design

This research applied an engineering-design and telemetry-based evaluation approach. The method was organized to identify available navigation telemetry, define route-monitoring variables, formulate deviation indicators, classify navigation conditions, and evaluate the resulting alert interpretation using simulation and real-world waypoint mission records. This workflow follows the need for real-time marine monitoring, autonomous mission supervision, and shore-based observation in unmanned maritime systems [5], [6].

The research workflow consists of five stages: telemetry source identification, data model definition, route deviation indicator formulation, navigation alert classification, and scenario-based evaluation. First, the available ASV telemetry streams are identified from the waypoint navigation, monitoring, and communication subsystems. Second, relevant navigation variables are selected to represent the vessel's route-following

TABLE 1.
COMPARISON OF PREVIOUS STUDIES AND THE PROPOSED CONTRIBUTION

Study Category	Main Focus	Main Data or Output	Limitation for Route Deviation Supervision
Modular autonomous-vehicle testing	Modular test framework for autonomous systems [19]	Test architecture and validation workflow	Does not address ASV route deviation alerting
Maritime IoT detection	Ship radius detection using IoT-based maritime application [20]	Radius-based detection and communication experiment	Does not evaluate planned mission route conformance
Buoy and shallow-water monitoring	Fixed marine monitoring platforms and buoy systems [21], [22]	Environmental data and communication performance	Not focused on mobile ASV route supervision
Real-time environmental observation	Real-time marine observation and impact monitoring [23]	Observation system and environmental data stream	Does not classify ASV navigation status
Fail-safe system	Battery and lost-link safety response [24]	Battery status, heartbeat detection, and safety action	Focuses on emergency response, not route deviation monitoring
Command and control unit	Sensor acquisition and water-observation interface [25]	GPS location, depth data, sensor data, and user interface	Does not convert waypoint telemetry into route alerts
Waypoint navigation	Autonomous waypoint mission execution [26]	Waypoint error, heading error, and field-test results	Focuses on onboard navigation performance
Route optimization	Multi-agent vehicle routing algorithm [27]	Route planning and allocation method	Does not address shore-side ASV telemetry supervision
IoT-based USV monitoring	Web-integrated USV monitoring and control [28]	Sensor accuracy, GPS monitoring, dashboard response	Does not classify route deviation conditions
This study	VTS-oriented route deviation monitoring	Waypoint-tracking telemetry and navigation alert levels	Provides shore-side interpretation of route deviation tendency

Based on this gap, the objective of this paper is to develop and evaluate a VTS-oriented route deviation monitoring method using waypoint-tracking telemetry. The novelty lies in three aspects. First, mission-relative telemetry is used to evaluate route conformance rather than only onboard navigation accuracy. Second,

condition. Third, waypoint-tracking indicators are formulated to evaluate deviation tendency, heading consistency, speed behavior, and telemetry availability. Fourth, these indicators are mapped into navigation alert levels. Finally, the proposed monitoring framework is evaluated using simulation and real-world waypoint

mission datasets obtained from a catamaran-type ASV testbed [25], [26].

B. System Architecture

The system architecture consists of three functional layers: onboard navigation, telemetry communication, and shore-side monitoring. The onboard layer includes the ASV platform, autopilot controller, companion computer, GPS receiver, inertial sensor, and propulsion system. The communication layer sends navigation telemetry from the vessel to the monitoring station through a real-time data stream. The shore-side layer receives the telemetry, calculates route-deviation indicators, and presents the navigation status to the operator.

The onboard navigation system remains responsible for

[16]. In addition, lightweight communication technologies and remote data streams have been widely used to support persistent maritime observation and unmanned vehicle supervision [17], [18]. In the proposed framework, these communication capabilities are used not as the main contribution, but as the data pipeline for navigation alert generation. Figure 1 illustrates the overall architecture of the proposed monitoring framework, covering the simulation validation stage, the real-world ASV testbed, waypoint telemetry transmission, and shore-side monitoring functions.

C. Telemetry Data Model

The proposed method uses waypoint-tracking telemetry as the primary data source. The selected variables consist of timestamp, active waypoint identification, planned waypoint coordinates, actual GPS coordinates, heading,

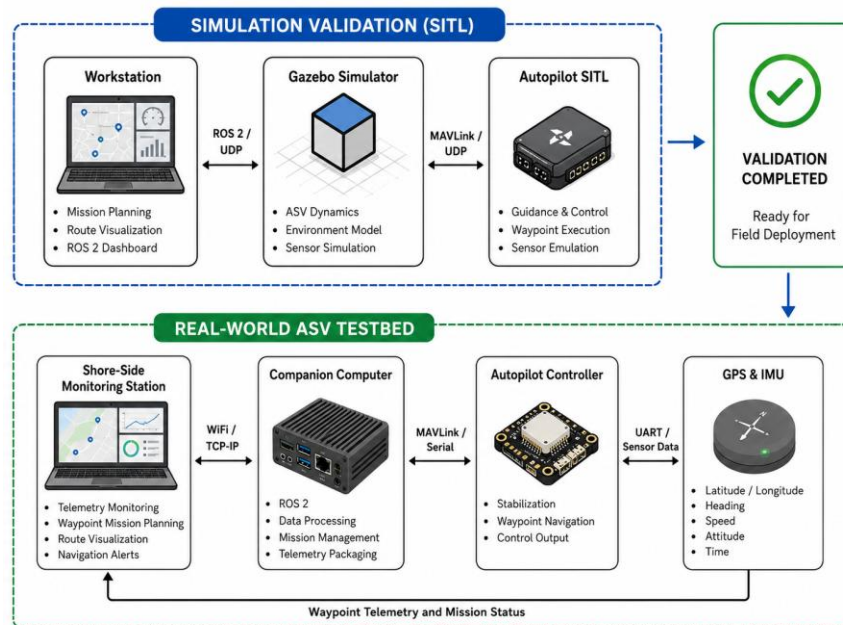


Figure 1. Overall architecture of the proposed VTS-oriented route deviation monitoring framework.

waypoint execution, stabilization, and propulsion control. The monitoring station does not generate steering or thrust commands; it evaluates whether the vessel movement remains consistent with the planned mission. This separation follows the general principle that autonomous vehicle systems require both onboard autonomy and supervisory monitoring to maintain operational awareness [7], [8].

The architecture is also consistent with recent ASV monitoring studies that combine sensor acquisition, telemetry transmission, and web-based visualization. Previous IoT-based marine monitoring systems have shown the importance of transmitting vessel and sensor data to a remote interface for operator supervision [15],

speed, mission mode, waypoint error, and telemetry status. These variables are selected because they represent the minimum information required for shore-side route deviation monitoring. Position and waypoint information are used to evaluate route-following progress, heading data are used to evaluate directional consistency, speed data are used to detect abnormal movement, and telemetry status is used to determine whether the monitoring layer receives sufficient data for operator supervision. Table 2 presents the telemetry variables used in the proposed route deviation monitoring framework and explains the function of each variable in supporting shore-side navigation supervision.

The telemetry variables are consistent with previous ASV and USV studies that use GPS, heading, mission

$$e_h = \text{wrap}(\psi_{\text{ref}} - \psi_{\text{actual}}) / \quad (2)$$

TABLE 2.
TELEMETRY VARIABLES USED IN THE PROPOSED ROUTE DEVIATION MONITORING FRAMEWORK

Variable	Description	Function in Monitoring Framework
Timestamp	Time of telemetry reception	Synchronizes route and alert analysis
Active waypoint ID	Current target waypoint in the mission	Identifies the navigation task being executed
Planned waypoint coordinates	Latitude and longitude of the target waypoint	Defines the intended mission reference
Actual GPS coordinates	Real-time ASV position	Evaluates route-following condition
Heading	Vessel orientation from compass or IMU	Evaluates directional consistency
Speed	Vessel speed during mission execution	Detects stagnation or abnormal motion
Mission mode	Autonomous, manual, hold, return, or fail-safe state	Interprets operational context
Waypoint error	Distance between actual position and waypoint target	Measures waypoint-tracking deviation
Telemetry status	Availability or interruption of data stream	Determines monitoring reliability
Alert level	Normal, caution, warning, or danger	Provides operator-oriented safety status

status, and communication data for navigation, monitoring, and control. Waypoint navigation experiments have commonly used waypoint error and heading error as the main metrics for evaluating mission execution [26]. Web-integrated monitoring and command systems have also used GPS location, sensor data, and dashboard-based display to support water observation and remote supervision [25], [28].

D. Route Deviation Indicators

Since cross-track error is not explicitly available in the current dataset, this study formulates route deviation monitoring based on waypoint-tracking telemetry. The route deviation tendency is evaluated using four indicators: waypoint error, heading deviation, speed behavior, and telemetry availability. These indicators are selected because they can be derived from the available mission logs and represent the main observable conditions for shore-side supervision.

The waypoint error is used to measure the distance between the actual ASV position and the active waypoint target. It is calculated using the Haversine distance between the current GPS coordinate and the target waypoint coordinate:

$$d_{wp} = 2R \arcsin \sqrt{\sin^2((\varphi_2 - \varphi_1)/2) + \cos \varphi_1 \cos \varphi_2 \sin^2((\lambda_2 - \lambda_1)/2)} \quad (1)$$

where d_{wp} is the waypoint error, R is the earth radius, φ_1 and λ_1 are the latitude and longitude of the actual ASV position, and φ_2 and λ_2 are the latitude and longitude of the target waypoint. This distance-based formulation is widely used in GPS-based waypoint navigation because it can estimate the geographic distance between two coordinate points on the earth surface [26].

The heading deviation is calculated from the difference between the desired bearing to the active waypoint and the actual vessel heading:

where e_h is the heading deviation, ψ_{ref} is the desired heading angle toward the active waypoint, and ψ_{actual} is the actual heading of the ASV. The wrap function is used to keep the angular difference within a valid circular heading range. This indicator is important because a vessel may still move toward a waypoint while showing directional inconsistency due to current, wind, steering delay, or control uncertainty [9], [10].

The speed behavior is evaluated to detect abnormal mission conditions such as stagnation, excessive speed reduction, or unexpected motion. Let v_{actual} be the measured vessel speed and v_{ref} be the expected mission speed. The normalized speed deviation is expressed as:

$$e_v = |v_{\text{actual}} - v_{\text{ref}}| / v_{\text{ref}} \quad (3)$$

where e_v is the normalized speed deviation. This indicator is not intended to evaluate propulsion performance, but to support route supervision by identifying whether the vessel movement remains consistent with the expected mission behavior. Speed abnormality is particularly important in autonomous operation because delayed movement or unexpected deceleration may indicate environmental disturbance, controller limitation, or mission interruption [11], [12].

Telemetry availability is evaluated by observing the continuity of incoming data. If telemetry packets are received within the allowed time interval, the monitoring condition is considered available. If no telemetry is received beyond the predefined timeout threshold, the monitoring status is degraded. This indicator is essential because shore-side supervision depends on data availability. Previous fail-safe studies have shown that lost-link and heartbeat monitoring are important indicators for operational safety in USV missions [24].

E. Navigation Alert Classification

The proposed framework converts waypoint-tracking indicators into four navigation alert levels: normal, caution, warning, and danger. The alert classification is rule-based because the objective is to provide transparent and interpretable information for shore-side operators. Rule-based classification is selected instead of a black-box model because route supervision must be understandable, auditable, and easy to configure for different operating areas. Table 3 summarizes the proposed navigation alert classification rule, which maps route-following conditions into four operator-oriented alert levels.

The alert logic combines the four indicators using a hierarchical rule. Telemetry loss and unexpected mission

G. Performance Metrics

The performance of the proposed monitoring framework is evaluated using four metrics: alert correctness, alert consistency, alert latency, and route supervision interpretability. Alert correctness indicates whether the generated alert corresponds to the expected condition in each scenario. Alert consistency evaluates whether similar navigation conditions produce the same alert level. Alert latency measures the time required for the system to generate an alert after telemetry data are received. Route supervision interpretability evaluates whether the alert level can be clearly interpreted by a

TABLE 3.
NAVIGATION ALERT CLASSIFICATION RULE

Alert Level	Condition Description	Operator Interpretation
Normal	Waypoint error, heading deviation, speed behavior, and telemetry status are within acceptable limits	Vessel movement is consistent with the planned mission
Caution	One indicator begins to deviate from the expected condition but remains below the critical limit	Operator should increase attention
Warning	Route-following inconsistency persists or two indicators deviate simultaneously	Operator should prepare intervention or mission adjustment
Danger	Telemetry is lost, mission mode changes unexpectedly, or severe deviation occurs	Operator should initiate emergency response or fail-safe action

mode changes are treated as high-priority conditions because they directly affect operator awareness. Waypoint error and heading deviation are then evaluated to determine whether the ASV remains consistent with the intended route. Speed behavior is used as a supporting indicator to distinguish between normal movement, delayed progress, and abnormal stopping. The overall alert level is determined by the highest risk condition among the monitored indicators.

F. Scenario-Based Evaluation

The proposed framework is evaluated using existing simulation and real-world waypoint mission datasets from a catamaran-type ASV testbed. The simulation dataset is used to observe the monitoring response under controlled conditions, while the real-world dataset is used to evaluate the framework under practical operating conditions. Previous waypoint navigation experiments reported that simulation and field testing are useful for validating autonomous mission execution and comparing the difference between ideal and real operating environments [26].

The evaluation focuses on three aspects. First, the baseline waypoint-tracking performance is analyzed using waypoint error and heading error. Second, the same telemetry variables are reinterpreted using the proposed alert classification framework. Third, the resulting alert levels are analyzed to determine whether the framework can provide meaningful shore-side supervision information. This evaluation approach allows the proposed study to extend previous navigation performance analysis into a VTS-oriented monitoring perspective without duplicating onboard controller development.

shore-side operator.

The proposed evaluation does not aim to replace onboard waypoint-navigation performance metrics. Instead, it complements them by translating waypoint-tracking telemetry into operational safety information. This distinction is important because VTS-oriented supervision requires interpretable status information rather than only numerical navigation error. Therefore, the proposed method bridges autonomous waypoint navigation and shore-side operator awareness through structured navigation alert generation [13], [14].

III. RESULTS AND DISCUSSION

A. Dataset and Telemetry Readiness

The evaluation used waypoint-navigation records and telemetry data from a catamaran-type ASV testbed. The records included simulation trials, real-world waypoint missions, telemetry communication logs, monitoring interface data, and onboard mission logging. Table 4 summarizes the datasets used to evaluate route deviation monitoring readiness.

The dataset contains the minimum variables required for route supervision: planned waypoint, actual position, heading, mission status, and telemetry availability. Previous waypoint-navigation evaluation used waypoint error and heading error as navigation performance indicators [26]. In this paper, those variables are treated as supervision indicators that help the operator interpret whether the ASV remains within an acceptable mission condition.

B. Baseline Waypoint-Tracking Performance

The waypoint-tracking performance was first analyzed to establish the baseline route-following capability of the ASV. The simulation dataset showed smaller navigation error because the environment did not include real disturbances such as wind, current, water-surface ripple, GPS uncertainty, and maneuvering dynamics. In contrast, the real-world dataset showed larger deviations because the ASV operated under practical field conditions. Table 5 summarizes the waypoint and heading performance used as the baseline for the proposed alert interpretation.

As shown in Table 5, the simulation results produced a mean waypoint error of 0.49 m and a mean heading error of 4.21°. These values indicate that the waypoint navigation system could maintain stable route-following behavior under controlled conditions. The waypoint error remained below 1 m in all simulation trials, showing that the simulated ASV could consistently approach the target waypoint locations.

The real-world results showed a mean waypoint error of 1.15 m and a mean heading error of 10.8°. The waypoint error ranged from 0.473 m to 1.837 m, while the heading error ranged from 0.4° to 17.4°. These values are higher than the simulation results, which is consistent with previous findings that field operation introduces GPS uncertainty, vehicle dynamics, and environmental disturbances [9], [10]. Nevertheless, all missions were completed successfully, indicating that the observed deviations represent route-following variation rather than complete mission failure.

C. Route Deviation Interpretation

The real-world mean waypoint error of 1.15 m remains acceptable for small ASV missions such as environmental monitoring, water-quality observation, and inland water inspection. However, shore-side operators need more than a numerical error value. The same waypoint deviation must be linked to the vessel's operational status, especially when heading deviation, speed anomaly, or telemetry degradation occurs during mission execution.

The proposed monitoring framework interprets route deviation tendency using waypoint error, heading deviation, speed behavior, mission status, and telemetry availability. In this evaluation, waypoint error and heading deviation served as the two primary indicators because they were directly available in the waypoint-navigation dataset. Speed behavior and telemetry availability were used as supporting indicators to determine whether the ASV movement and monitoring condition remained operationally valid. This interpretation is aligned with the VTS-oriented concept in which vessel monitoring should support route awareness and operator decision-making, not only position visualization [13], [14].

The difference between simulation and real-world results also shows the importance of field-based route supervision. In simulation, the heading error remained

within a narrow range, indicating predictable vehicle orientation. In real-world testing, however, the heading error increased up to 17.4°, which suggests that the vessel may still progress toward the waypoint while experiencing directional inconsistency. For shore-side monitoring, this condition is important because a moderate waypoint error combined with a high heading deviation may indicate a developing route deviation tendency.

D. Navigation Alert Generation

The proposed alert logic classified the route-following condition into four levels: normal, caution, warning, and danger. The classification was based on the relationship between waypoint error, heading deviation, speed behavior, mission status, and telemetry availability. Since no telemetry loss or emergency mission state was observed in the evaluated waypoint-navigation dataset, the danger level was reserved for severe deviation, unexpected mode change, or loss of telemetry. Table 6 presents the navigation alert interpretation derived from the evaluated waypoint-tracking conditions.

Table 6 shows that the simulation trials were classified as normal because the waypoint error remained below 1 m and the mean heading error was 4.21°. Several real-world conditions also remained normal when waypoint and heading deviations were low. Larger waypoint error or heading deviation shifted the status to caution or warning, depending on the severity and persistence of the deviation.

The most important result is not only the absolute magnitude of waypoint error, but the operational meaning of the deviation. A waypoint error of approximately 1 m may still be acceptable for mission completion, but if it is accompanied by increasing heading deviation, delayed progress, or unstable telemetry, the operator should receive a higher alert level. This interpretation makes the framework more suitable for shore-side supervision than a conventional waypoint-performance table alone.

E. Telemetry and Monitoring Support

The proposed framework depends on the availability of real-time telemetry because navigation alerts cannot be generated without position, heading, mission status, and communication data. Previous monitoring and communication studies have shown that web-based telemetry infrastructure can support real-time supervision through browser-based interfaces, MQTT/WebSocket communication, and dashboard visualization [21], [22]. In the evaluated ASV system, telemetry information such as vehicle position, heading orientation, waypoint status, and mission progress could be transmitted and monitored with low delay [26].

The web-integrated monitoring infrastructure also supports the proposed framework by providing real-time

waypoint missions were completed. Therefore, larger navigation errors in the field should not automatically be

TABLE 4.
EXPERIMENTAL DATASETS USED FOR ROUTE DEVIATION MONITORING EVALUATION

Dataset	Data Source	Main Variables	Function in This Study
Simulation waypoint mission	SITL and Gazebo-based mission validation	Target waypoint, actual position, waypoint error, heading error	Provides baseline route-following behavior under controlled conditions
Real-world waypoint mission	Catamaran-type ASV field test	Target waypoint, actual GPS position, heading, waypoint error, mission status	Evaluates route deviation tendency under practical operating conditions
Telemetry monitoring stream	Web-based monitoring and telemetry infrastructure	Position, heading, speed, mission status, communication response	Supports shore-side supervision and alert delivery
Monitoring and control interface	Browser-based operator station	Mission visualization, vehicle state, operator display	Provides the interface layer for navigation alert presentation
Mission logging record	Onboard logging infrastructure	Timestamped sensor and navigation records	Supports post-mission analysis and route supervision validation

data visualization and operator interaction. Previous

interpreted as mission failure. They instead define an

TABLE 5.
EXPERIMENTAL DATASETS USED FOR ROUTE DEVIATION MONITORING EVALUATION

Test Condition	Number of Trials	Waypoint Error Range	Mean Waypoint Error	Heading Error Range	Mean Heading Error	Mission Completion
Simulation waypoint mission	10	0.31–0.63 m	0.49 m	3.5°–5.1°	4.21°	Completed
Real-world waypoint mission	10	0.473–1.837 m	1.15 m	0.4°–17.4°	10.8°	Completed

TABLE 6.
EXPERIMENTAL DATASETS USED FOR ROUTE DEVIATION MONITORING EVALUATION

Condition	Observed Indicator	Alert Level	Operator Interpretation
Simulation route following	Waypoint error below 1 m and heading error near 4°	Normal	The ASV follows the planned mission under controlled conditions
Real-world low deviation	Waypoint error below 1 m and low heading deviation	Normal	The ASV remains consistent with the planned route
Real-world moderate deviation	Waypoint error around 1.0–1.5 m or heading deviation above simulation baseline	Caution	Operator should increase attention to route-following behavior
Real-world high heading deviation	Heading error above 10° while mission remains active	Warning	Operator should monitor possible route deviation or prepare intervention
Severe route inconsistency	Large waypoint error, abnormal speed behavior, unexpected mode change, or telemetry loss	Danger	Operator should initiate intervention or fail-safe response

testing reported GPS positional error, data-fetching response, and data-transmission performance that are sufficient for general marine observation and remote monitoring applications [28]. Therefore, the proposed route deviation monitoring framework can be implemented as an additional interpretation layer above the existing monitoring infrastructure rather than as a replacement for the telemetry system.

F. Discussion of VTS-Oriented Route Supervision

The difference between simulation and field performance provides the first important finding. The mean waypoint error increased from 0.49 m in simulation to 1.15 m during field operation, corresponding to an increase of approximately 134.7%. The mean heading error increased from 4.21° to 10.8°, or approximately 156.5%. Despite these increases, all

intermediate operational condition in which the vehicle remains functional but deserves greater supervisory attention.

This observation also explains why a single waypoint-error threshold is insufficient for route supervision. A vehicle may remain relatively close to the target waypoint while temporarily exhibiting a large heading deviation, or it may show moderate positional error while its speed decreases and mission progress slows. Combining waypoint error with heading deviation, speed behavior, mission state, and telemetry continuity provides a richer representation of route conformance than waypoint distance alone. Environmental disturbances, positioning uncertainty, and vehicle dynamics reported in previous ASV studies further support the need for multi-indicator interpretation [9], [10].

The finding differs from conventional path-following research, where navigation error is primarily used to evaluate or improve controller performance [29], [30]. Maritime trajectory-surveillance studies, on the other hand, commonly identify deviations from historical or learned vessel traffic patterns [31], [32]. The contribution of the present work lies between these two approaches: the reference is an explicitly planned ASV waypoint mission, while the output is navigation-status information intended for operational supervision. This allows existing waypoint telemetry to serve not only as a controller-performance record but also as a mission-conformance indicator.

The current alert thresholds should nevertheless be interpreted as preliminary operational rules rather than universal safety limits. The field results were obtained from a small ASV in restricted waters, and GPS uncertainty, environmental conditions, vessel size, mission speed, and waypoint spacing can affect the observed deviation. Additional experiments are therefore required before the same thresholds can be transferred to other platforms or operating areas. Continuous route-segment deviation, larger field datasets, and operator-response testing would provide stronger validation of the alert boundaries.

G. Limitations

Several limitations should be acknowledged. First, the current evaluation uses waypoint error and heading deviation rather than cross-track error because continuous route-segment deviation data were not explicitly available in the evaluated dataset. Second, the alert thresholds were formulated as a rule-based classification and should be refined through additional field trials in more diverse operating conditions. Third, the evaluated dataset represents small ASV missions in restricted water environments, so the results should not be generalized directly to large autonomous vessels or high-density traffic areas. Future work should include navigation corridor modeling, continuous trajectory-based route deviation calculation, operator response-time analysis, and integration with collision-risk surveillance.

IV. CONCLUSION

This study aimed to develop and evaluate a VTS-oriented route deviation monitoring method using waypoint-tracking telemetry from autonomous surface vehicle missions. The evaluation used ten simulation trials and ten real-world waypoint missions and considered waypoint error, heading deviation, speed behavior, mission status, and telemetry availability as route-conformance indicators.

The simulation trials produced a mean waypoint error of 0.49 m and a mean heading error of 4.21° , whereas the field trials produced 1.15 m and 10.8° , respectively. Although field operation increased both navigation errors, all missions were completed. The results therefore show that route supervision should consider the combined behavior of several navigation variables rather

than interpret waypoint error alone as an indication of mission success or failure.

The main contribution is the use of mission-relative waypoint telemetry as operational route-conformance information for remote ASV supervision. The method provides an intermediate interpretation between onboard waypoint-navigation performance and conventional VTS trajectory monitoring. Its current limitation is that the assessment relies on waypoint and heading errors rather than continuous cross-track or route-segment deviation. Future work should validate continuous trajectory deviation, adaptive alert thresholds, larger field datasets, and operator response to navigation alerts.

REFERENCES

- [1] J. E. Manley, "Unmanned maritime vehicles: 20 years of commercial and technical evolution," in Proc. OCEANS 2016 MTS/IEEE Monterey, Monterey, CA, USA, 2016, pp. 1–6.
- [2] Y. Gu, J. C. Goez, M. Guajardo, and S. W. Wallace, "Autonomous vessels: State of the art and potential opportunities in logistics," *International Transactions in Operational Research*, vol. 28, no. 4, pp. 1706–1739, 2021.
- [3] U. K. Verfuss et al., "A review of unmanned vehicles for the detection and monitoring of marine fauna," *Marine Pollution Bulletin*, vol. 140, pp. 17–29, 2019.
- [4] O. Lewicka et al., "Integration data model of the bathymetric monitoring system for shallow waterbodies using UAV and USV platforms," *Remote Sensing*, vol. 14, no. 16, p. 4075, 2022.
- [5] G. Xu, Y. Shi, X. Sun, and W. Shen, "Internet of things in marine environment monitoring: A review," *Sensors*, vol. 19, no. 7, p. 1711, 2019.
- [6] A. Barbie et al., "Developing an underwater network of ocean observation systems with digital twin prototypes: A field report from the Baltic Sea," *IEEE Internet Computing*, vol. 26, no. 3, pp. 33–42, 2022.
- [7] M. R. Benjamin, H. Schmidt, P. M. Newman, and J. J. Leonard, "Nested autonomy for unmanned marine vehicles with MOOS-IvP," *Journal of Field Robotics*, vol. 27, no. 6, pp. 834–875, 2010.
- [8] G. Wu, D. Li, H. Ding, D. Shi, and B. Han, "An overview of developments and challenges for unmanned surface vehicle autonomous berthing," *Complex & Intelligent Systems*, vol. 10, no. 1, pp. 981–1003, 2024.
- [9] E. I. Sarda, H. Qu, I. R. Bertaska, and K. D. von Ellenrieder, "Station-keeping control of an unmanned surface vehicle exposed to current and wind disturbances," *Ocean Engineering*, vol. 127, pp. 305–324, 2016.
- [10] W. B. Klinger, I. R. Bertaska, K. D. von Ellenrieder, and M. R. Dhanak, "Control of an unmanned surface vehicle with uncertain displacement and drag," *IEEE Journal of Oceanic Engineering*, vol. 42, no. 2, pp. 458–476, 2017.
- [11] J. D. Setiawan, M. A. Septiawan, M. Ariyanto, W. Caesarendra, M. Munadi, and M. Sulowicz, "Development and performance measurement of an affordable unmanned surface vehicle," *Automation*, vol. 3, no. 1, pp. 2–21, 2022.
- [12] H. Niu, Z. Ji, P. Liguori, H. Yin, and J. Carrasco, "Design, integration and sea trials of 3D printed unmanned aerial vehicle and unmanned surface vehicle for cooperative missions," *Journal of Intelligent & Robotic Systems*, vol. 103, no. 3, pp. 1–18, 2021.
- [13] International Association of Marine Aids to Navigation and Lighthouse Authorities, IALA Guideline G1089 on Provision of Vessel Traffic Services, IALA, 2022.
- [14] International Maritime Organization, "Regulatory scoping exercise for the use of maritime autonomous surface ships," IMO Maritime Safety Committee, MSC.1/Circ.1638, 2021.
- [15] S. L. Ullo and G. R. Sinha, "Advances in smart environment monitoring systems using IoT and sensors," *Sensors*, vol. 20, no. 11, p. 3113, 2020.
- [16] D. T. Vo, X. P. Nguyen, T. D. Nguyen, R. Hidayat, T. T. Huynh, and D. T. Nguyen, "A review on the internet of thing technologies in controlling ocean environment," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 47, no. 1, pp. 10064–10082, 2021.

- [17] C. Albaladejo, P. Sánchez, A. Iborra, F. Soto, J. A. López, and R. Torres, "Wireless sensor networks for oceanographic monitoring: A systematic review," *Sensors*, vol. 10, no. 7, pp. 6948–6968, 2010.
- [18] A. Dallocio, G. Quintana-Diaz, E. Honoré-Livermore, J. L. Garrett, R. Birkeland, and T. A. Johansen, "A satellite-USV system for persistent observation of mesoscale oceanographic phenomena," *Remote Sensing*, vol. 13, no. 16, p. 3229, 2021.
- [19] M. Akbaş, M. Menase, S. Verma, and R. Razdan, "PolyFlows: Modular test framework design for autonomous vehicles," in *Proc. IEEE International Conference on Mobility, Operations, Services and Technologies*, Dallas, TX, USA, 2024, pp. 50–59.
- [20] A. S. Arifin, M. Suryanegara, T. S. Firdaus, and Asvial, "IoT-based maritime application: An experiment of ship radius detection," in *Proc. ACM International Conference*, New York, NY, USA, 2017, pp. 1–6.
- [21] A. Albaladejo, F. Soto, R. Torres, P. Sánchez, and J. A. López, "A low-cost sensor buoy system for monitoring shallow marine environments," *Sensors*, vol. 12, no. 7, pp. 9613–9634, 2012.
- [22] A. Majumder, M. Losito, S. Paramasivam, A. Kumar, and G. Gatto, "Buoys for marine weather data monitoring and LoRaWAN communication," *Ocean Engineering*, vol. 313, p. 119521, 2024.
- [23] O. R. Godø, J. Klungsøyr, S. Meier, E. Tenningen, A. Purser, and L. Thomsen, "Real time observation system for monitoring environmental impact on marine ecosystems from oil drilling operations," *Marine Pollution Bulletin*, vol. 84, no. 1–2, pp. 236–250, 2014.
- [24] S. A. Sukarno, H. Nuruliman, and Ridwan, "Design and implementation independent battery and lost-link fail-safe module for USV safety," *International Journal of Marine Engineering Innovation and Research*, vol. 11, no. 2, 2026.
- [25] S. A. Sukarno, H. Rudiansyah, H. T. Maulana, M. Kadir, and F. S. Adi, "Design and development of a command and control unit (CCU) on an unmanned surface vehicle (USV) for water observation," *International Journal of Marine Engineering Innovation and Research*, vol. 10, no. 4, pp. 1124–1132, 2025, doi: 10.12962/j25481479.v10i4.
- [26] Lu, Z.; Li, W.; Zhang, X.; Wang, J.; Zhuang, Z.; Liu, C. Design and Testing of an Autonomous Navigation Unmanned Surface Vehicle for Buoy Inspection. *J. Mar. Sci. Eng.* 2024.
- [27] S. A. Sukarno, R. B. Atitallah, and M. Djemai, "Approximation algorithm for 3-dimensional vehicle routing problem for fleet of multi-agents," in *Proc. 6th International Conference on Control Engineering & Information Technology*, Istanbul, Turkey, 2018, pp. 1–6, doi: 10.1109/CEIT.2018.8751928.
- [28] A. A. Priadi, T. Cahyadi, L. Barasa, S. A. Sukarno, N. Suranta, and M. Yando, "Development of IoT-based monitoring for unmanned surface vessels (USV)," *Journal of Engineering Science and Technology*, Special Issue on STIPCON2024, vol. 20, no. 5, pp. 1–10, 2025.
- [29] H. Xu and C. Guedes Soares, "Vector field path following for surface marine vessel and parameter identification based on LS-SVM," *Ocean Engineering*, vol. 113, pp. 151–161, 2016, doi: 10.1016/j.oceaneng.2015.12.037.
- [30] Q. Wang, M. Zhong, G. Shi, J. Zhao, and C. Bai, "Route planning and tracking for ships based on the ECDIS platform," *IEEE Access*, vol. 9, pp. 71754–71762, 2021, doi: 10.1109/ACCESS.2021.3078899.
- [31] N. Antunes, J. C. Ferreira, J. Pereira, and J. Rosa, "Grid-based vessel deviation from route identification with unsupervised learning," *Applied Sciences*, vol. 12, no. 21, Art. no. 11112, 2022, doi: 10.3390/app122111112.
- [32] T. Stach, Y. Kinkel, M. Constapel, and H.-C. Burmeister, "Maritime anomaly detection for Vessel Traffic Services: A survey," *Journal of Marine Science and Engineering*, vol. 11, no. 6, Art. no. 1174, 2023, doi: 10.3390/jmse11061174.