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Enhanced Underwater AIS for Communication-Based Collision Avoidance in Autonomous Underwater Vehicles

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The increasing complexity of underwater environments due to expanding marine research, exploration, and industrial activities has elevated the collision risk for autonomous underwater vehicles (AUVs). Traditional sensor-based collision avoidance (COLAV) systems can be constrained by environmental factors such as acoustic noise and low visibility, prompting more robust solutions. One promising approach is data sharing via the JANUS-based Underwater AIS (UAIS) protocol. UAIS could also inform decision-making when making underwater COLREG-compliant systems. This paper proposes several UAIS enhancements—including fields for uncertainty and manoeuvrability, dynamic data transmission, and hybrid acoustic–optical communication—and addresses associated security needs using encryption and authentication measures. To quantify UAIS's potential impact, two Bayesian Networks (BNs) estimate how UAIS data can reduce an AUV's risk of losing navigational control. Results suggest a notable drop in collision risk when UAIS is integrated. Nonetheless, challenges remain regarding cost, standardization, and the possibility of overreliance on AIS data. The proposed system marks a promising step toward safer and more efficient underwater navigation through communication-based COLAV solutions.

Keywords: Underwater communication, Collision avoidance, Data-sharing protocols, Autonomous Underwater Vehicles, Maritime safety, Underwater Navigation, Underwater AIS, Situational Awareness, Acoustics

1. Introduction

AUVs traditionally operate singly, performing polar exploration, subsea pipeline inspection, and environmental monitoring. However, increased marine research, exploration, and industrial activity have crowded underwater environments, elevating collision risks and complicating navigation.

Currently, AUV COLAV systems rely on onboard sensors like acoustic sensors (e.g., Forward-Looking Sonar (FLS), multibeam echo sounders (MBES)) and optical sensors (e.g., Light Detection And Ranging (LiDAR), cameras). Although effective, factors such as acoustic noise, low visibility, and signal attenuation constrain their reliability (Kot, 2022). As underwater environments become more dynamic and unpredictable, relying solely on sensors may be insufficient.

Data-sharing systems that exchange navigational and operational data among underwater assets offer a promising solution. Shared navigational data can bolster situational awareness to prevent collisions, while operational data on vessel status, planned paths, and manoeuvres enable more informed navigation, akin to the International Regulations for Preventing Collisions at Sea (COLREG) for surface vessels (International Maritime Organization, 2024).

This paper explores enhancing underwater COLAV through data-sharing. Section 2 reviews existing systems, with a focus on the JANUS-based UAIS. UAIS has seen use in maritime settings, often addressing submerged-to-surface interactions (Ferreira et al., 2018), but it has not been fully examined for underwater COLAV. Section 3 proposes modifications to UAIS to improve its use in underwater COLAV. Improvements focus on refining message content to better support collision avoidance, increasing transmission efficiency, and strengthening security. Section 4 then presents two BN models: one for an AUV relying solely on sensors and one incorporating UAIS. Their comparison highlights the potential collision risk reductions via UAIS. Section 5 discusses the findings, and Section 6 concludes with limitations and suggested future work. These results represent a step toward safer underwater navigation via communication-based COLAV.

2. Existing Protocols for Underwater Communication

An underwater communication protocol defines the rules and methods by which marine systems—such as underwater sensor networks, vehicles, and infrastructure—exchange data using acoustic, optical, or radio-frequency signals. Developing such a protocol from scratch is resource-intensive and inefficient. Established protocols offer tested solutions, and standardized approaches promote broader adoption and interoperability among diverse underwater vehicles and systems. Below we examine existing underwater communication protocols to determine whether any can serve as a foundation for our work.

Many of the considered protocols were unsuitable due to hardware dependencies, proprietary restrictions, or narrow operational focus. While ultimately not selected, one promising candidate was the SWIGacoustic standard, developed by the Subsea Wireless Group (SWiG) for offshore energy applications (Smerdon et al., 2016). Based on the open NATO standard JANUS (Potter et al., 2014), SWIGacoustic introduces industry-specific modifications, limiting its broader applicability. While specialized protocols serve their intended domains well, they may not fully address the needs of a general communication-based collision avoidance system. Our solution must support vehicles outside existing protocol frameworks, provide redundancy if specialized systems fail, and ensure interoperability in increasingly diverse underwater environments.

Given the constraints, JANUS (STANAG 4748) emerged as a viable option. JANUS (STANAG 4748) is an open standard designed to facilitate basic communication across different underwater platforms (Potter et al., 2014). It includes a JANUS-based UAIS, facilitating the exchange of essential navigational data, such as identification, position, depth and velocity. While JANUS-based UAIS may not match proprietary systems in speed, its openness and interoperability makes it a suitable base for our proposed communication protocol for collision avoidance. For details on JANUS UAIS message structures and technical specifications, see ”JANUS Community” [online] (2023); Petroccia et al. (2016, 2017).

3. A Modified UAIS

While UAIS provides a robust framework for underwater data sharing, enhancements are needed to optimize it for COLAV. Key improvements focus on refining message content to better support collision avoidance, increasing transmission efficiency, and strengthening security—all while preserving the generality of JANUS AIS. The following sections outline the proposed modifications.

3.1. *Assets*

The UAIS system currently supports a diverse range of assets, including submarines, AUVs, ships, airplanes, UAVs (Unmanned aerial vehicles), USVs (Unmanned surface vehicles), buoys, and bottom nodes, as defined by the standard (”JANUS Community” [online], 2023). Transmitting asset types could enhance underwater COLAV by improving operational coordination in line with an underwater version of COLREG principles (for more information about COLREG, please visit the IMO’s website (International Maritime Organization, 2024)).

This categorization can be expanded to include additional assets such as floating infrastructure (e.g., wind farms, oil rigs, and floating platforms) (Ferreira et al., 2019; Petroccia et al., 2017; Smerdon et al., 2016), underwater infrastructure (e.g., moored platforms, submerged cables, and pipelines) (Petroccia et al., 2017), debris (e.g., lost cargo containers and fishing nets), or marine animals (e.g., whales). Although these assets cannot actively avoid collisions, they could broadcast their positions unidirectionally.

Incorporating these additional asset types could further enhance safety and operational benefits. As the cost of acoustic transponders continues to decrease with advancing technology (Rak, 2024), integrating these systems into a wider range of assets becomes increasingly feasible.

3.2. *Technology*

UAIS enables transmissions up to tens of kilometres but is limited by low data rates (kbps) and high latency due to narrow bandwidth and low frequencies (Zhu et al., 2020). Alternative methods, such as Radio Frequency (RF) and Underwater Wireless Optical Communication (UWOC), offer different trade-offs. RF provides moderate data rates (Mbps) and lower latency but is restricted to short ranges (tens of meters) due to signal attenuation in seawater. UWOC delivers high data rates (Gbps), low latency, and high power efficiency, though it is limited to hundreds of meters and affected by water turbidity (Zhu et al., 2020).

Hybrid communication systems, which combine these technologies, show promise for adapting to varying subsea conditions (Smerdon et al., 2016). For UAIS, a hybrid approach could use acoustic communication for long-range updates and switch to optical communication at closer ranges when both vehicles have optical modems equipped. This leverages optical communication's high data rates and power efficiency, allowing more frequent updates in critical situations and enhancing real-time responsiveness.

3.3. *Data*

Efficient COLAV requires balancing high data update rates, precision, relevant content, and energy efficiency. While frequent, precise updates are essential in high-risk scenarios, transmitting unnecessary data can cause interference, noise, and excessive power consumption. To address this, UAIS can implement dynamic data transmission strategies that adjust both the rate and content of messages based on the operational context.

UAIS currently transmits critical information via Baseline and Cargo Packets, including asset type, position (latitude and longitude), course over ground (CoG) or true heading, depth, and navigational status ("JANUS Community" [online], 2023). However, this data may include uncertainties in position, velocity, and depth. Adding fields for data uncertainty would allow other vehicles to account for potential inaccuracies. Additionally, incorporating data types such as planned paths (e.g., waypoints) and manoeuvrability (e.g., turning radius) can enhance situational awareness by providing insights into other vehicles' intended movements and collision-avoidance capabilities (Ferreira et al., 2019).

Not all data fields are equally critical in every scenario. In low-risk or low-density environments, static message content can lead to redundant transmissions, reducing bandwidth and energy efficiency. A more effective approach involves using multiple AIS message types tailored to convey specific data (Ferreira et al., 2019). For example, assets could periodically send comprehensive messages with all relevant details while sending frequent updates that focus only on dynamic data like position and velocity. Static information, such as vessel type, could be referenced by ID to minimize repeated transmissions.

Adopting a dynamic message transmission rate can improve efficiency and situational awareness. In high-density or high-risk scenarios, messages should be transmitted more frequently to provide timely updates (Ferreira et al., 2019), whereas in low-density or low-risk environments, reducing the transmission rate can minimize interference and power usage. Factors such as vehicle speed and proximity to potential collision points can dictate both the frequency and content of messages. UAIS already employs variable resolutions for data fields, such as depth (1m increments near the surface to 75m at greater depths) and speed (0.705° increments for CoG). This piecewise quantization can be dynamically adjusted across all data types based on situational criticality, allowing lower precision for long-range, low-risk transmissions to reduce data size.

3.4. *Safety and security*

Safety and security are critical yet competing priorities in underwater communication systems like UAIS. While broad data sharing is essential for COLAV, it must be protected against malicious threats such as spoofing and jamming (Androjna et al., 2021). Implementing lightweight encryption and authentication protocols, such as CCM and AEGIS (Petroccia and Alves, 2024), can mitigate these risks without significantly impacting bandwidth or latency. Additionally, interference mitigation strategies like Venila enhance reliability in high-traffic environments (Hamilton et al., 2022).

For robotic systems, robust fallback mechanisms are vital when communication data is unavailable. In scenarios involving stealth assets or non-broadcasting vehicles, AUVs must rely on onboard sensors (e.g., sonar, LIDAR) and predictive modelling to detect and avoid unseen objects. Developing these fallback strategies based on relevant risk models ensures continued safety, although detailed mechanisms are beyond this paper's scope.

4. Bayesian Networks for Preliminary Risk Reduction Analysis

BNs are directed acyclic graphs used for risk assessment in various domains (Haugen and Kristiansen, 2022). This section presents two BNs: one representing the collision risk when an AUV relies solely on sensors, and another incorporating both sensors and UAIS. The comparison estimates the potential risk reduction introduced by UAIS and highlights key risk factors. Following the methodology in Bremnes et al. (2025, 2020); Thieme and Utne (2017), the steps are:

(i) Define the context and aim of the model
(ii) Hazard identification
(iii) Constructing the BN
(iv) Quantify BN and conditional probability tables (CPTs)

4.1. *Context and purpose of the model*

The model aims to demonstrate the difference in an AUV's COLAV capability with and without the proposed UAIS communication system.

Figure 1 illustrates a scenario where UAIS informs COLAV decisions. AUV1 navigates to a docking station, avoiding collisions with AUV2 and a swarm of AUV3s while following the shortest path. It is assumed the AUVs make decisions, informed by available data, following Underwater COLREG rules.

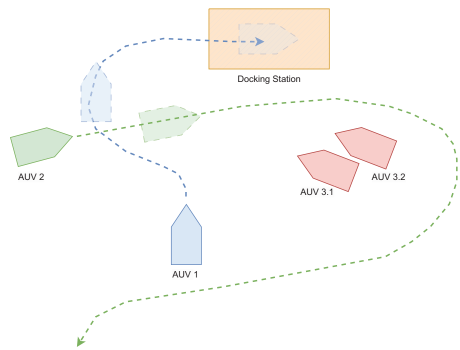

Fig. 1. AUV1 is docking safely by avoiding the collision course with AUV2.

Haugen and Kristiansen (2022) models the probability of collisions between two vessels as shown in Eq. (1):

$$P_a = P_c \times P_i \tag{1}$$

where

- P_a is the probability of accident per passage
- P_c is the probability of losing navigational control of the vessel per passage
- P_i is the impact probability

Assuming P_a is constant with and without UAIS, only P_c is modelled in the BNs to estimate the potential collision risk reduction.

The AUV system includes propulsion, navigation computer, obstacle detection, and decision-making for COLAV.

In Scenario 1, the AUV uses optical and acoustic sensors to detect obstacle positions, speed, heading, and size. In scenario 2, the AUV adds an acoustic UAIS system, which adds additional estimates of an obstacle's position, speed, heading, and their uncertainty, along with details such as its size, manoeuvrability, type, and navigational status.

4.2. *Hazard identification*

In line with previous risk assessment research on autonomous maritime operations (e.g., Guo et al. (2021)), the focus is on the hazardous event *Loss of Control* (HE1), which can ultimately lead to a collision. Building on established studies, four system-level hazards (H) and one Risk Influencing Factor (RIF) are defined, reflecting the AUVs' critical system components that could trigger HE1:

- **H1 - Propulsion System Failure:** Mechanical or electrical faults.
- **H2 - Obstacle Detection Failure:** System fails to detect or properly localize obstacles.
- **H3 - Decision System Failure:** System fails to make correct collision-avoidance decisions.
- **RIF1 - System Failure:** General software issues.

4.3. *Constructing the BNs*

4.3.1. *BN1: AUV with sensors*

Figure 2 shows the first BN, designed to capture the probability of HE1 when the AUV relies solely on sensors.

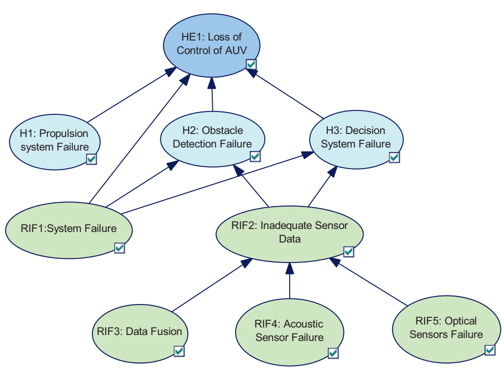

Fig. 2. BN1 illustrating the risk of loss of control for an AUV equipped with optical and acoustic sensors.

The top event, HE1, is influenced directly by three hazards, H1, H2 and H3, and the overarching RIF1, as described in the above subsection. Of these, H1 and RIF1 are included for a holistic risk perspective, but not broken down further. H2 and H3 are in BN1 influenced by the same factors, RIF1 and RIF2. RIF2, representing inadequate sensor data, are influenced by the three RIFs:

- **RIF3 - Data Fusion**: Failures in systems and algorithms responsible for processing and combining data from different sources.
- **RIF4 - Acoustic Sensors Failure**: Hardware, software and environmental factors that cause the acoustic sensors to produce unreliable or no data.
- **RIF5 - Optical Sensors Failure**: Hardware, software and environmental factors that cause the optical sensors to produce unreliable or no data.

4.3.2. *BN2: AUV with sensors and UAIS*

Figure 3 shows the second BN, designed to capture the probability of HE1 when the AUV relies on sensors and UAIS.

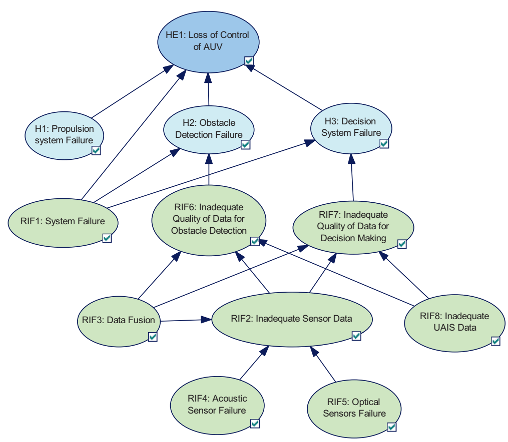

Fig. 3. BN2 illustrating the risk of loss of control for an AUV with integrated UAIS, optical, and acoustic sensors.

BN2 extends BN1 by introducing RIF6 and RIF7, which reflect the quality of fused sensor- and UAIS data for obstacle detection (H2) and decision-making (H3), respectively. While RIF6 focuses on obstacle detection accuracy, RIF7 accounts for decision-making, potentially influenced by underwater COLREG compliance. Both RIF6 and RIF7 depend on RIF2, RIF3, and a new node, RIF8 UAIS data quality.

RIF8 captures potential UAIS-specific failures, including hardware or software issues, environmental factors (e.g., acoustic interference), and operational constraints such as latency or congestion from multiple vehicles using UAIS.

4.4. *Quantify BN and CPTs*

The BNs are quantified by assigning probabilities to each node and choosing the CPTs. The CPTs in BNs define the probability of a child node's states based on its parent nodes, quantifying relationships and determining outcome likelihoods under given conditions. Failure probabilities are estimates derived from literature and adapted to the AUV system. Table 1 summarizes the estimated frequencies used to populate the nodes in BN1 and BN2.

RIF5 and RIF8 are estimated relative to RIF4, as optical sensors are generally less reliable than acoustic sensors for underwater detection, particularly at longer ranges. Similarly, acoustic communication (RIF8) is assumed to be more challenging than sonar-based obstacle detection (RIF4) due to additional factors like latency and interference. RIF3 is chosen such that it is not too low. This would overestimate UAIS's relative risk-reduction potential. RIF3 is chosen to reflect a conservatively high estimate.

Table 1. Estimated failure rates for BN nodes.

Node	Frequency (pr. mission)	Source
H1	4.3 e-05	Guo et al. (2021)
RIF1	2 e-06	Guo et al. (2021)
RIF3	0.05	Estimate
RIF4	0.005	Yang et al. (2023)
RIF5	0.01	Estimate
RIF8	0.02	Estimate

CPTs are used to describe the causal relationships between variables in BN models. The state of all nodes are either Failure (F) or Success (S). The CPTs similar in both scenarios are HE1, H2 and RIF2. For HE1 and H2: If all their inputs are successes, they succeed. For RIF2: It fails if Data Fusion (RIF3) fails. If RIF3 is assumed a success, the CPT of RIF2 looks like table 2. RIF6 is identical. Assuming RIF3 is a success, the result of RIF6 (dependent on RIF2 and RIF8) also looks like table 2.

Table 2. CPT for RIF2 (RIF4, RIF5) and RIF6 (RIF2 and RIF8).

RIF4 or RIF2	F		S	
RIF5 or RIF8	F	S	F	S
F	1	0	0	0
S	0	1	1	1

In scenario 1, with sensors only, H3 succeeds with a 0.9 chance if all input nodes succeed. The CPT for this is attached in Table 3. The 0.1 chance of failing represents that only sensor data may not be sufficient when doing decision-making following COLREG. RIF2 fails if Data Fusion (RIF3) fails. If RIF3 is assumed to be a success, the CPT looks like Table 2.

Table 3. CPT for H3, Scenario 1.

RIF1	F		S	
RIF2	F	S	F	S
F	1	1	1	0.1
S	0	0	0	0.9

In scenario 2, with sensors and UAIS, H3 succeeds if both inputs (RIF1, RIF7) succeed. RIF7 fails if Data Fusion (RIF3) fails. The CPT, assuming RIF3 is a success, is included in Figure 4. Here, if UAIS (RIF8) fails while sensors succeed (RIF2), there is a 0.1 chance of failure. This again accounts for the probability of wrong decision-making if one only has sensor data.

4.5. *Results and sensitivity analysis*

With the assumptions outlined in the prior sections, the calculated probability of *loss of control* in the two BNs are:

Table 4. CPT for RIF7.

RIF2	F		S	
RIF8	F	S	F	S
F	1	0	0.1	0
S	0	1	0.9	1

- **Scenario 1:** 0.14
- **Scenario 2:** 0.05

When UAIS is integrated, a significant decrease in the probability of *loss of control* is observed.

When analysing the marginal probability of the nodes, two nodes are of special interest. The first is H3, the main source of lower HE1 probability when comparing the two scenarios. H2 does not show the same level of change. The assumption that UAIS is necessary for making a *guaranteed* correct decision (H3) is therefore central to our results.

The second is RIF3, Data Fusion. By changing the probability of Data Fusion errors in this node, one can change the probability of HE1 significantly. Lowering its failure probability amplifies the benefit of adding UAIS, while a higher failure probability diminishes it. This shows the importance of choosing this number deliberately high to avoid overstating UAIS's relative risk-reduction potential.

5. Discussion

The proposed communication-based COLAV system offers the potential for enhancing underwater COLAV, but challenges remain. Not all vehicles have acoustic modems, and while UAIS does not require a specific modem type, acoustic communication can be costly. Advances in low-cost acoustic modems (Rak, 2024) may spur wider adoption as underwater traffic grows.

Overreliance on AIS data poses risks; inaccurate or misleading signals could lead both human operators and autonomous systems to overlook other critical inputs, compromising safety (Wu et al., 2022). Future work may explore cooperative COLAV or a "bilingual" approach, using UAIS for initial contact and proprietary protocols for complex exchanges, which could enhance flexibility while preserving UAIS's global reach (Petroccia et al., 2015). Such additions could be a positive addition but could also complicate the standardization efforts.

Extensive field testing is key to validating the systems' effectiveness. Finally, risk analysis and modelling, e.g., supervisory risk control (see e.g., Bremnes et al. (2020)), may also provide input to the communication strategy, the frequency of messaging, and fallback mechanisms.

Preliminary BN results indicate a notable reduction in collision risk with UAIS integration, though they rely on simplifying assumptions. Future studies should incorporate additional environmental and operational variables (e.g., latency, traffic density, visibility) and refine probability estimates. Despite these limitations, the BN analysis affirms UAIS's potential to enhance COLAV.

6. Conclusion

This paper presented the UAIS communication framework and proposes several modifications to enhance its suitability for underwater COLAV. Key modifications include integrating additional asset types, incorporating new data fields such as manoeuvrability and data uncertainty, implementing dynamic data transmission strategies, and adopting hybrid acoustic–optical communication technologies. To ensure system integrity, encryption and authentication mechanisms are also recommended to mitigate security vulnerabilities like spoofing and interference.

To evaluate the potential impact of these modifications, two BNs were developed: one modelling the probability of loss of control for an AUV relying solely on onboard sensors, and another incorporating both sensors and the enhanced UAIS. The comparative analysis revealed a significant reduction in collision risk when UAIS is integrated, with the probability of loss of control decreasing from 0.14 to 0.05. This result underscores the potential effectiveness of communication-based COLAV in enhancing underwater navigational safety.

Overall, the findings highlight the promising role of enhanced UAIS in advancing safer and more efficient underwater navigation. By leveraging communication-based strategies, AUVs can achieve higher levels of situational awareness and operational coordination, thereby mitigating collision risks in increasingly congested and dynamic underwater environments.

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