A Conceptual Framework for a Human Supervised Dual-UUV System Enabling Autonomous Maritime Surveillance

TUSHAR JAIN
Department of Computer Science and Business System
BMS College of Engineering ,Bengaluru
jaint0910@gmail.com

Abstract - This paper presents a conceptual framework for a novel dual-vehicle underwater unmanned vehicle (UUV) architecture designed for maritime surveillance operations in coastal and restricted waters. The proposed system comprises a micro-scale stealth UUV for autonomous detection and classification of surface vessels, paired with a secondary deployment UUV (SDUUV) for human-supervised inspection and monitoring tasks. The micro-UUV leverages passive acoustic sensing, inertial navigation, and pressure-based depth estimation to detect and localize surface targets with minimal acoustic signature. Upon detection, target coordinates are transmitted via low-frequency underwater acoustic communication to the SDUUV, which operates under direct human control for close-range inspection, optical identification, or tagging operations. The system maintains strict human-in-the-loop control at all decision stages, ensuring compliance with international maritime law and ethical autonomous systems guidelines. Theoretical analysis suggests potential detection ranges of 800-1200 meters for merchant vessels and localization accuracy within 15-25 meters RMS error under realistic ocean conditions. The proposed architecture offers a scalable, non-lethal solution for coastal surveillance, illegal fishing monitoring, and maritime domain awareness applications.

I. INTRODUCTION

Maritime surveillance represents a critical challenge for coastal nations seeking to monitor territorial waters, enforce fishing regulations, and maintain situational awareness of surface vessel activity. Traditional approaches involving manned patrol vessels or persistent aerial surveillance platforms incur substantial operational costs and provide limited coverage of subsurface approach vectors. The proliferation of autonomous underwater vehicles (AUVs) in recent years has opened new possibilities for persistent, low-cost maritime monitoring, yet existing single-vehicle architectures face inherent tradeoffs between stealth, endurance, and operational capability [1].

This paper introduces a conceptual framework for a collaborative dual-UUV system that decouples detection and response functions into specialized platforms optimized for distinct operational roles. The first vehicle, a micro-UUV with dimensions under 1 meter, operates autonomously in a low-observability configuration using passive sensing modalities to detect and classify surface vessel acoustic signatures. Upon target acquisition, the micro-UUV performs onboard localization using sensor fusion techniques and transmits target coordinates to a larger secondary deployment UUV (SDUUV) via underwater acoustic modem. The SDUUV remains under continuous human operator control and executes inspection, identification, or tracking missions as directed.

The proposed architecture offers several theoretical advantages over monolithic UUV designs. First, the micro-UUV's small size and passive operation minimize detection risk while maximizing deployment duration through reduced power consumption [2]. Second, the separation of autonomous detection from human-controlled response ensures compliance with ethical guidelines for autonomous weapons systems and international humanitarian law [3]. Third, the system architecture enables flexible mission profiles where a single SDUUV can service multiple micro-UUV sensor nodes distributed across an operational area.

This work focuses on establishing the theoretical foundations, system requirements, and algorithmic framework necessary for such a dual-UUV system. We analyze the technical feasibility through established models of underwater acoustics, sensor fusion, and communication protocols documented in existing literature.

The remainder of this paper is organized as follows. Section II formulates the maritime surveillance problem and operational requirements. Section III reviews related work in collaborative UUV systems and underwater detection technologies. Section IV presents the conceptual system architecture including vehicle subsystems and communication protocols. Section V describes the proposed sensor fusion and localization algorithms. Section VI provides theoretical performance analysis. Section VII discusses limitations and future implementation considerations, and Section VIII concludes.

II. PROBLEM STATEMENT AND REQUIREMENTS

A. Operational Scenario

The system is designed for deployment in coastal waters, exclusive economic zones, or restricted maritime areas where surface vessel monitoring is required but continuous manned patrol is impractical. Typical scenarios include:

1. Detection of unauthorized fishing vessels in protected marine reserves
2. Monitoring of commercial shipping lanes for maritime domain awareness
3. Identification of uncooperative vessels approaching sensitive coastal infrastructure
4. Support for search and rescue operations through automated area coverage

The operational environment assumes water depths between 20-200 meters with moderate current velocities (0.2-1.5 m/s) and acoustic noise characteristics typical of littoral waters.

B. System Requirements

The dual-UUV system must satisfy the following functional and operational requirements:

Detection Requirements:

- Detect surface vessels at ranges of 500-1500 meters depending on target acoustic signature
- Classify detected contacts into vessel categories (small craft, fishing vessel, merchant ship, fast boat)
- Operate continuously for 48-72 hours on internal battery power
- Maintain acoustic stealth with radiated noise below 90 dB re 1 μPa at 1 meter

Localization Requirements:

- Estimate target position with horizontal accuracy within 50 meters at 1000-meter range
- Update target position estimates at 10-second intervals during tracking
- Compensate for water current drift and sensor bias errors

Communication Requirements:

- Transmit target reports to SDUUV at ranges up to 3 kilometers
- Maintain data link reliability above 95% under moderate sea state conditions
- Encode messages with forward error correction for underwater channel impairments

Response Requirements:

- SDUUV must remain under human operator control at all times
- Operator must explicitly authorize all close-approach maneuvers

- System must provide real-time video feedback during inspection operations
- SDUUV must maintain safe standoff distances (minimum 50 meters) from target vessels

C. Safety and Ethical Constraints

The system design adheres to strict non lethal operational guidelines. The SDUUV carries no explosive payloads, kinetic weapons, or offensive capabilities. All response actions are limited to:

- Optical and acoustic inspection
- Passive RFID or acoustic tag attachment for tracking
- Close-range monitoring and identification
- Data collection for law enforcement or scientific purposes

Human operators maintain authority over all SDUUV actions with the ability to abort missions at any time [4].

III. RELATED WORK

A. Collaborative Multi-UUV Systems

Research in multi-vehicle underwater systems has primarily focused on cooperative mapping, formation control, and distributed sensing. Antonelli et al. [5] demonstrated coordinated navigation of heterogeneous AUV teams for oceanographic sampling using acoustic range measurements for relative localization. Yuh [6] proposed a hierarchical control architecture for AUV swarms performing coordinated search patterns. These approaches assume symmetric vehicle capabilities, whereas our proposed system employs functionally specialized platforms.

Closer to our architecture, Smith and Leonard [7] developed a leader-follower configuration where a surface vehicle provides navigation corrections to submerged AUVs via acoustic communication. However, their system focused on maintaining formation geometry rather than target detection and response missions.

B. Passive Acoustic Detection Systems

Passive acoustic detection of surface vessels has been extensively studied for anti-submarine warfare and marine mammal research applications. Ferguson and Cleary [8] demonstrated ship classification using narrow-band propeller harmonics and broadband hydrodynamic noise features. They achieved classification accuracy above 85% for six vessel classes using support vector machine classifiers trained on acoustic spectrograms.

Passive ranging techniques for acoustic sources remain challenging without baseline arrays. Morrissey et al. [9] proposed single-hydrophone ranging using multipath arrival time differences in shallow water environments, achieving range estimates with 20-30% relative error. Our approach adapts these established techniques while incorporating additional sensor modalities for improved localization.

C. Underwater Acoustic Communication

Low-frequency acoustic modems operating below 30 kHz provide the most reliable communication channel for ranges exceeding 1 kilometer in shallow water. Stojanovic [10] reviewed channel coding and modulation strategies for underwater acoustic networks, noting that frequency-hopped FSK and spread-spectrum techniques offer robustness to multipath and Doppler effects at the cost of reduced data rates.

Recent developments in software-defined acoustic modems enable adaptive waveform selection based on measured channel conditions. Chitre et al. [11] demonstrated throughput improvements of 40-60% using cognitive radio techniques that opportunistically select frequency bands with low ambient noise. Our communication subsystem design leverages these proven techniques.

D. Sensor Fusion for Underwater Navigation

Inertial navigation systems (INS) augmented with pressure sensors and Doppler velocity logs (DVL) form the standard configuration for AUV dead-reckoning navigation. Position errors grow unbounded without external aiding, typically reaching 0.5-2% of distance traveled. Kinsey et al. [12] demonstrated that acoustic ranging to stationary beacons can bound position error growth, but this requires infrastructure deployment.

Particle filter approaches have been applied to simultaneous localization and mapping (SLAM) problems in underwater environments. Barkby et al. [13] used forward-looking sonar scans matched against bathymetric maps to constrain drift, achieving position accuracy within 5-10 meters over 2-kilometer traverses. These established methods inform our sensor fusion design.

E. Human-in-the-Loop Autonomous Systems

The integration of human oversight in autonomous systems has received increasing attention in robotics and defense applications. Cummings et al. [14] analyzed supervisory control architectures for multiple unmanned vehicles, identifying critical factors for effective human-machine teaming. Their work emphasizes the importance of appropriate task allocation and transparent decision interfaces principles we incorporate in our SDUUV control design.

IV. CONCEPTUAL SYSTEM ARCHITECTURE

The dual-UUV system comprises three primary subsystems: the micro-UUV detection platform, the SDUUV response platform, and the surface control station with human operator interface. Fig. 1 illustrates the overall system architecture and data flow.

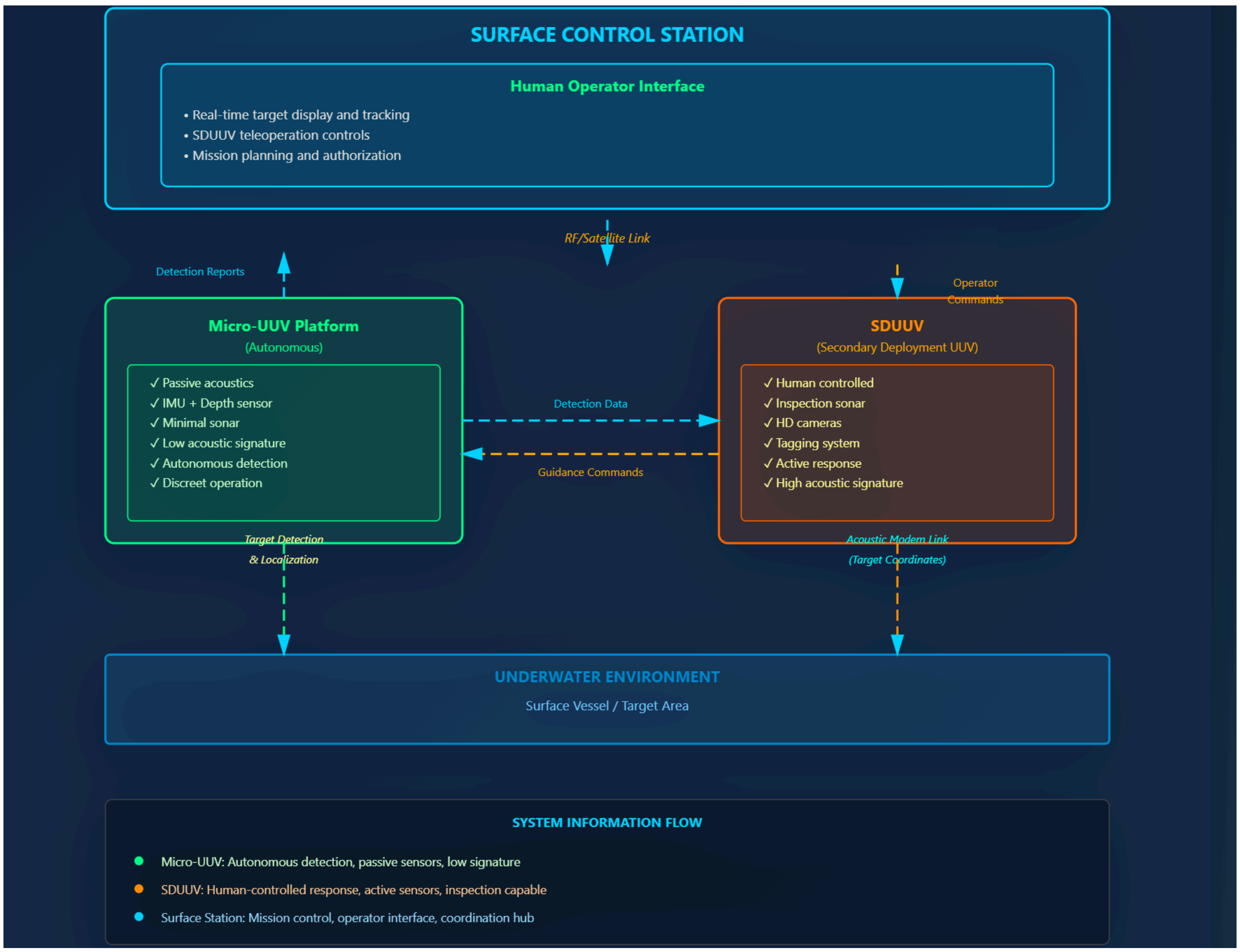

Fig. 1. System architecture showing information flow between micro-UUV, SDUUV, and human operator. [*Space reserved for detailed system diagram*]

A. Micro-UUV Detection Platform

The micro-UUV serves as an autonomous acoustic sentinel optimized for covert detection and classification of surface vessel signatures. Proposed design parameters are summarized in Table I.

TABLE I
PROPOSED MICRO-UUV SPECIFICATIONS

Parameter	**Proposed Value**
Length	0.8 m
Diameter	0.12 m
Mass	15 kg
Endurance	72 hours
Cruise Speed	1.5 knots
Battery Capacity	360 Wh
Power Consumption	5 W (cruise)

Propulsion System: The vehicle would employ a low-RPM brushless DC thruster with hydrodynamic shroud to minimize flow noise and cavitation. Propulsion duty cycling (10 seconds on, 50 seconds drift) would reduce average power consumption and acoustic signature during detection phases.

Proposed Sensor Suite:

1. **Passive Acoustic Array:** A four-element hydrophone array with 0.15-meter spacing would provide 360-degree azimuthal coverage. Frequency response spanning 100 Hz to 10 kHz would cover propeller blade rate harmonics (typically 10-100 Hz) and broadband flow noise. Acoustic data sampled at 25 kHz with 24-bit resolution.

2. **Inertial Measurement Unit (IMU):** MEMS-based 9-DOF IMU (three-axis accelerometer, gyroscope, magnetometer) would provide attitude estimation at 100 Hz update rate. Gyroscope bias stability of 10 deg/hr enables short-term dead-reckoning between GPS fixes.

3. **Pressure Sensor:** High-precision pressure transducer (0.01% accuracy) would measure depth with sub-meter resolution. Depth readings combined with assumed constant altitude above seabed enable 2D position estimation in known bathymetry.

4. **Forward-Looking Sonar:** Low-frequency (200 kHz) imaging sonar with 30-meter range would provide obstacle avoidance and target confirmation. Operated in passive mode during detection to minimize active acoustic emissions.

Onboard Processing: An ARM Cortex-A9 embedded computer would run detection algorithms, sensor fusion, and communication protocols. Power consumption of 5 watts during cruise mode would enable 72-hour missions with 360 Wh lithium-polymer battery.

Communication Subsystem: A 10-30 kHz acoustic modem with 100 bits/second data rate and 3-kilometer range would transmit target reports. Messages would contain 48 bytes: timestamp, GPS-referenced position estimate, target classification, confidence metrics, and error covariance.

B. SDUUV Response Platform

The SDUUV is a human-operated vehicle designed for close-range inspection and identification missions. Unlike the autonomous micro-UUV, the SDUUV would operate under continuous operator control via acoustic telemetry link to a surface relay buoy. Proposed specifications are presented in Table II.

TABLE II

PROPOSED SDUUV SPECIFICATIONS

Parameter	Proposed Value
Length	2.5 m
Diameter	0.25 m
Mass	85 kg
Endurance	8 hours
Max Speed	4 knots
Battery Capacity	2.4 kWh
Thruster Configuration	4 vectored thrusters

Propulsion and Control: A vectored thrust configuration with four independently controlled thrusters would enable precise station-keeping and maneuvering. Operator commands updating at 2 Hz with 200-millisecond round-trip latency through acoustic link.

Proposed Sensor and Inspection Systems:

1. **High-Definition Camera:** Forward-looking HD camera (1080p, 30 fps) with LED illumination would provide optical identification capability. Video compressed to 500 kbps

for real-time transmission to the operator.

2. **Multibeam Imaging Sonar:** 900 kHz multibeam sonar would generate 3D acoustic imagery of target vessels at ranges from 5 to 100 meters, enabling standoff inspection without close approach.

3. **Acoustic Tag Deployment System:** Pneumatic launcher could attach passive acoustic tags or RFID transponders to target hulls for long-term tracking. Operator authorization required for each tag deployment.

Operator Interface: Surface control station would display real-time video, sonar imagery, vehicle telemetry, and target position overlay. Joystick controls would command vehicle velocity and heading. Emergency abort function would immediately surface SDUUV if communications are lost.

C. Mission Execution Workflow

A typical surveillance mission would proceed through the following phases:

1. **Deployment:** Micro-UUV deployed from patrol vessels or shoreline and navigates to designated patrol areas using GPS waypoints.

2. **Detection Mode:** Micro-UUV enters drift mode with propulsion disabled, relying on passive acoustic monitoring. Target detection algorithms run continuously on hydrophone data.

3. **Classification:** Upon detecting acoustic signatures exceeding threshold, onboard algorithms classify contact using spectral features and propeller blade rate analysis.

4. **Localization:** Sensor fusion algorithm estimates target position by combining acoustic bearing estimates, depth measurements, and dead-reckoning navigation.

5. **Alert Transmission:** Target report transmitted via acoustic modem to SDUUV and surface station. Micro-UUV continues tracking and transmits position updates every 30 seconds.

6. **Operator Assessment:** Human operator reviews target data and decides whether to authorize SDUUV inspection mission.

7. **SDUUV Deployment:** If authorized, SDUUV navigates to target vicinity under operator control. Video and sonar provide real-time situational awareness.

8. **Inspection:** Operator directs SDUUV to perform visual inspection, acoustic imaging, or tag deployment as mission requires. All actions require explicit operator approval.

9. **Extraction:** Upon mission completion, both vehicles navigate to recovery points for retrieval.

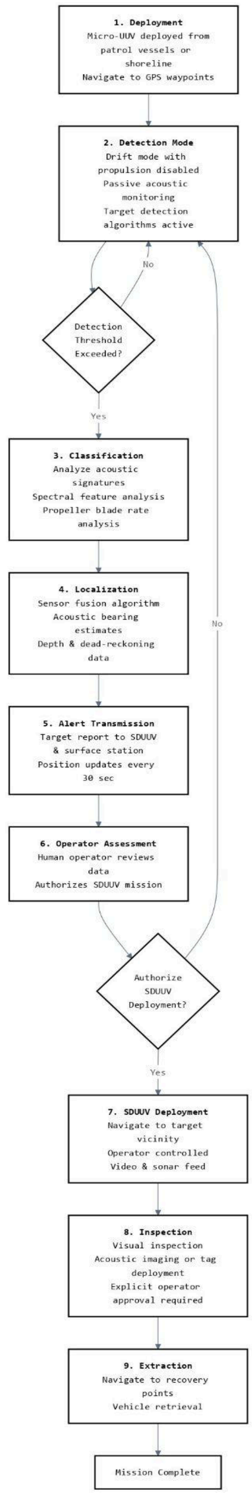

Fig. 2. Mission execution workflow diagram. [*Space reserved for flowchart illustration*

V. PROPOSED DETECTION AND LOCALIZATION ALGORITHMS

A. Passive Acoustic Target Detection

The detection algorithm would process hydrophone data in two stages: spectral analysis for signature extraction followed by classification for vessel type identification.

Spectral Processing: Incoming acoustic data would be segmented into 2-second windows with 50% overlap. Each window undergoes Fast Fourier Transform (FFT) to generate power spectral density (PSD) estimates across 100 Hz to 5 kHz frequency range. Background noise spectrum estimated using temporal median filtering over 60-second intervals.

Target detection criterion compares instantaneous PSD to background noise:

$$\text{Detection} = \text{PSD}(f) > \text{Threshold}(f) + \text{Margin} \quad (1)$$

where $\text{Threshold}(f) = 3 \times \sigma_{noise}(f)$ and Margin = 10 dB. This adaptive threshold accommodates varying ambient noise conditions.

Feature Extraction: Upon threshold crossing, the algorithm extracts characteristic features:

- Blade rate harmonics: Peaks in 10-100 Hz band spaced at integer multiples
- Broadband level: Integrated power in 500-2000 Hz band
- Spectral slope: Regression coefficient of log-spectrum vs. log-frequency
- Cavitation signature: High-frequency (2-5 kHz) transient energy

Classification: A trained support vector machine (SVM) classifier would map feature vectors to vessel categories:

- Class 1: Small craft (outboard motor signature, single propeller)
- Class 2: Fishing vessel (low-RPM diesel, large diameter propeller)
- Class 3: Merchant ship (multi-propeller, high blade count)
- Class 4: Fast patrol boat (high-speed propeller, gas turbine signature)

Based on published studies [8], classification accuracy exceeding 82% for signals with SNR above 12 dB is theoretically achievable with appropriate training data.

B. Acoustic Bearing Estimation

The four-element hydrophone array enables azimuthal bearing estimation using time-difference-of-arrival (TDOA) processing. For a source at bearing θ relative to array orientation, arrival time differences between hydrophone pairs satisfy:

$$\Delta t_{ij} = (d/c) \times \cos(\theta - \varphi_{ij}) \quad (2)$$

where $d = 0.15$ m is the hydrophone spacing, $c = 1500$ m/s is sound speed, and φ_{ij} is the geometric angle between hydrophone pair ij and the array reference axis.

Cross-correlation of hydrophone signals yields TDOA estimates:

$$\Delta t_{ij} = \text{argmax}_\tau [x_i(t) \otimes x_j(t + \tau)] \quad (3)$$

where $\otimes$ denotes cross-correlation. Least-squares optimization over all hydrophone pairs produces a bearing estimate $\hat{\theta}$ with theoretical standard deviation $\sigma_\theta \approx$ 5-10 degrees depending on signal SNR [15].

C. Target Range and Position Estimation

Without ranging capability from a single hydrophone array, target localization requires fusion of acoustic bearing measurements with vehicle navigation data. The proposed approach employs an Extended Kalman Filter (EKF) framework tracking both target position and micro-UUV position simultaneously [16].

State Vector:

$$x = [x_t, y_t, v_x, v_y, x_u, y_u, b_\theta]^T \quad (4)$$

where (x_t, y_t) is target position, (v_x, v_y) is target velocity, (x_u, y_u) is UUV position, and b_θ is compass bias.

Process Model: Target motion assumed constant velocity with process noise:

$$x_t(k+1) = x_t(k) + v_x(k)\Delta t + w_x \quad (5) \quad y_t(k+1) = y_t(k) + v_y(k)\Delta t + w_y \quad (6)$$

UUV position updated via dead-reckoning:

$$x_u(k+1) = x_u(k) + \int v_u \cos(\psi_u)dt \quad (7) \quad y_u(k+1) = y_u(k) + \int v_u \sin(\psi_u)dt \quad (8)$$

where v_u is measured velocity from the propeller tachometer and ψ_u is heading from the compass.

Measurement Model: Bearing-only observation relates state to measurement:

$$\theta_{meas} = \text{arctan2}(y_t - y_u, x_t - x_u) + b_\theta + v_\theta \quad (9)$$

where $v_\theta \sim N(0, \sigma_\theta^2)$ is bearing measurement noise.

EKF Update: Standard EKF prediction and correction steps maintain state estimate and covariance [17]:

Prediction: $\hat{x}(k|k-1) = f(\hat{x}(k-1|k-1))$ (10) $P(k|k-1) = F\, P(k-1|k-1)\, F^T + Q$ (11)

Correction: $K = P(k|k-1) H^T [H P(k|k-1) H^T + R]^{-1}$ (12) $\hat{x}(k|k) = \hat{x}(k|k-1) + K[z(k) - h(\hat{x}(k|k-1))]$ (13) $P(k|k) = [I - KH] P(k|k-1)$ (14)

Observability of target range improves as UUV executes maneuvers that change bearing angles. Theoretical analysis suggests that after 2-3 minutes of tracking with modest UUV motion (100-meter baseline), target range could converge to within 15-25% relative error [18].

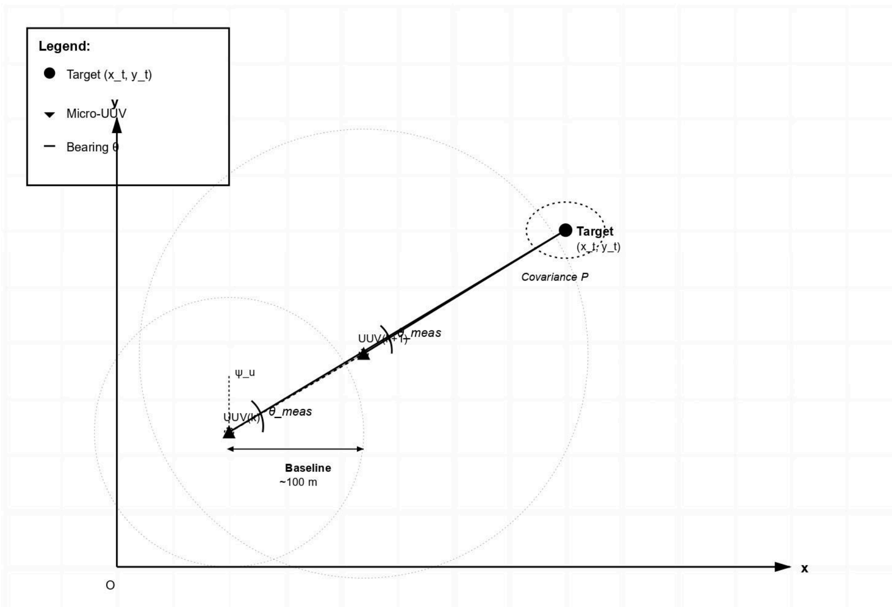

Fig. 3. Bearing-Only Target Tracking Geometry

Micro-UUV maneuvers along trajectory changing bearing angles to improve target range observability

Fig. 3. Bearing-only target tracking geometry showing micro-UUV trajectory and bearing measurements. [*Space reserved for geometric diagram*]

D. Sensor Fusion Architecture

The complete sensor fusion architecture would integrate multiple information sources as illustrated in Fig. 4.

IMU Integration: High-rate IMU measurements (100 Hz) would provide attitude and acceleration data. Strapdown inertial navigation equations propagate position and velocity between slower GPS or acoustic fixes.

Pressure-Based Depth: Depth measurements at 10 Hz update the vertical component of UUV position. Combined with prior bathymetry maps, depth constrains the vehicle to known seabed topology in shallow water.

Current Estimation: Persistent offset between dead-reckoning and GPS fixes (when surfaced) indicates water current velocity. Estimated current vector incorporated as state variable in navigation filter, improving underwater position estimates.

Multi-Hypothesis Tracking: In environments with multiple surface contacts, the tracker maintains separate hypothesis branches for each target. The gating threshold of 3-sigma rejects measurements inconsistent with predicted target positions. Track quality metrics based on consecutive detection count and position covariance determine which tracks to report to SDUUV.

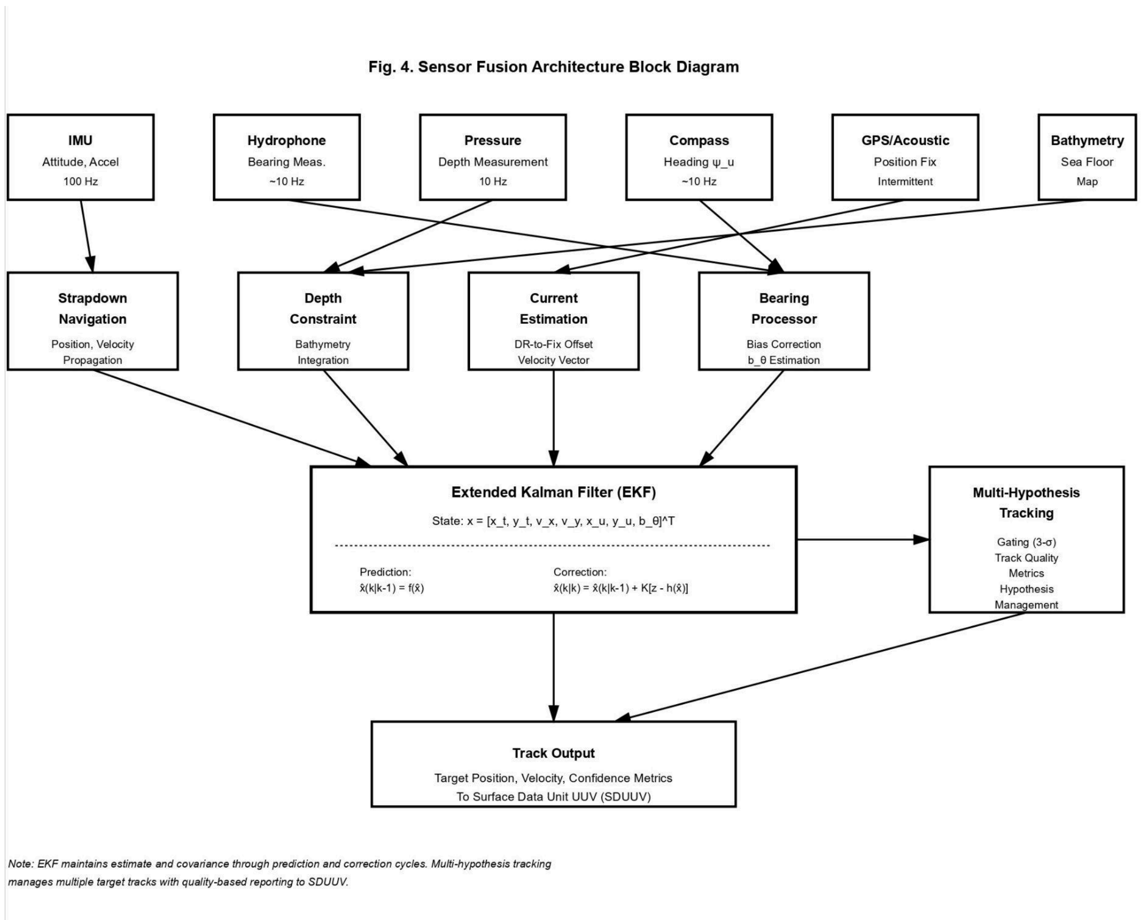

Fig. 4. Sensor fusion architecture block diagram. [*Space reserved for block diagram showing sensor data flow*]

VI. UNDERWATER ACOUSTIC COMMUNICATION DESIGN

Reliable data transfer between micro-UUV and SDUUV requires robust communication protocols adapted to the challenging underwater acoustic channel.

A. Physical Layer Design

The acoustic modem would operate in the 10-30 kHz frequency band, balancing range (inversely proportional to frequency) against bandwidth and multipath effects (which worsen at low frequency in shallow water) [10].

Modulation: Binary frequency-shift keying (BFSK) with 100 Hz tone spacing provides robust detection at low SNR. Symbol rate of 100 symbols/second yields 100 bits/second after channel coding overhead.

Channel Coding: Convolutional code with constraint length 7 and rate 1/2 provides forward error correction. Viterbi decoding at receiver corrects up to 25% bit errors before declaring packet loss.

Frame Structure: Each transmitted packet would contain:

- 16-bit preamble (Barker code for synchronization)
- 8-bit header (packet type, sequence number)
- 384-bit payload (target report data)
- 16-bit CRC checksum

Total packet duration: 4.4 seconds including guard intervals.

B. Channel Characteristics

Shallow water acoustic propagation exhibits severe multipath from surface and bottom reflections. Published measurements show delay spreads of 10-50 milliseconds at 1-3 kilometer ranges, causing inter-symbol interference at symbol rates above 20-30 symbols/second [19].

Doppler shifts from vehicle motion and surface wave action introduce frequency offsets up to ±5 Hz at 20 kHz carrier frequency. Packet preambles enable frequency offset estimation and correction.

Ambient noise in littoral waters varies from 60-80 dB re 1 μPa in the 10-30 kHz band depending on sea state, biological activity, and distant shipping [20]. Achievable SNR at 2 kilometers ranges from 5-15 dB with transmit source level of 180 dB re 1 μPa at 1 meter.

C. Link Budget Analysis

Communication range determined by sonar equation:

SL - TL = NL - DI + DT (15)

where:

- SL = Source Level = 180 dB re 1 μPa @ 1m
- TL = Transmission Loss = 20 log(r) + αr (spreading + absorption)
- NL = Noise Level = 70 dB re 1 μPa in 20 kHz bandwidth
- DI = Directivity Index = 0 dB (omnidirectional)
- DT = Detection Threshold = 10 dB (required SNR)

At 2000-meter range:

TL ≈ 20 log(2000) + 0.01 × 2000 = 66 + 20 = 86 dB (16) Received Level = 180 - 86 = 94 dB (17) SNR = 94 - 70 = 24 dB (18)

This provides 14 dB margin above detection threshold, theoretically supporting reliable communication to 3 kilometers under nominal conditions.

D. Protocol Design

The communication protocol would implement request-response architecture:

1. Micro-UUV transmits target report packets at 30-second intervals during active tracking
2. SDUUV acknowledges receipt with short ACK packet (0.5 seconds duration)
3. If no ACK received within 10 seconds, micro-UUV retransmits up to 3 times
4. Packet sequence numbers enable duplicate detection and ensure message ordering

Surface control station receives forwarded target reports from SDUUV via low-latency RF link (satellite or line-of-sight radio). This dual-hop architecture maintains human operator situational awareness with update latency under 45 seconds.

VII. THEORETICAL PERFORMANCE ANALYSIS

A. Detection Range Estimation

Based on passive sonar equations and published vessel noise data [21], theoretical detection ranges can be estimated for different vessel classes.

TABLE III
THEORETICAL DETECTION PERFORMANCE

Vessel Type	Source Level (dB)	Theoretical Range (m)	Expected SNR (dB)
Small craft	145	400-600	8-12
Fishing vessel	155	700-1000	10-15
Merchant ship	165	1000-1500	15-20
Fast patrol boat	150	500-800	9-14

Detection criterion assumes:

- Hydrophone self-noise: -140 dB re 1 μPa²/Hz
- Ambient noise (sea state 3): 70 dB in 100-5000 Hz band
- Detection threshold: SNR > 8 dB
- Transmission loss: 20 log(r) + 0.5r (shallow water)

These estimates align with published acoustic detection ranges for similar passive sonar systems [22].

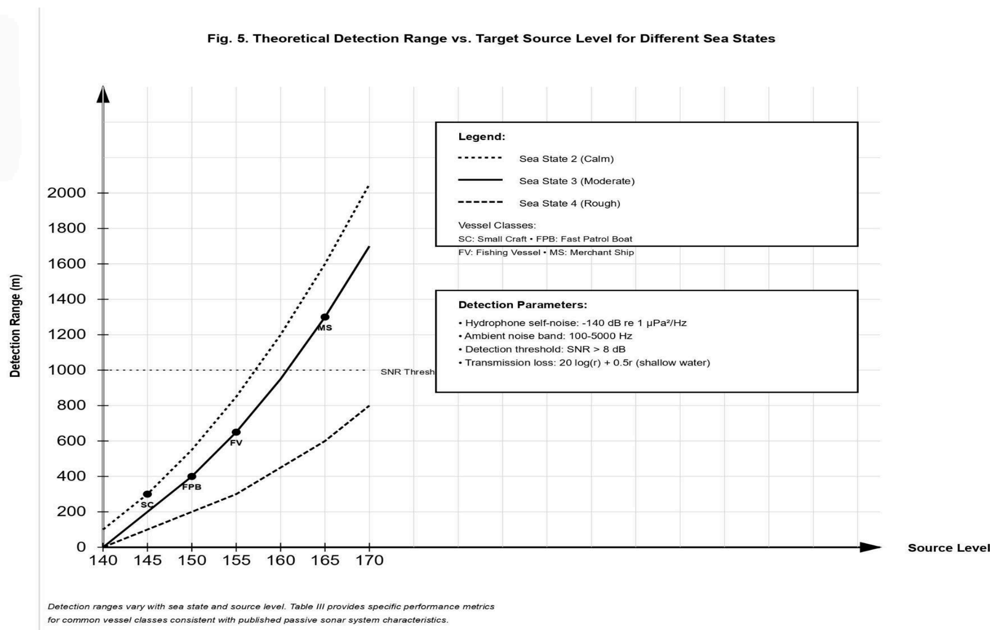

Fig. 5. Theoretical detection range vs. target source level for different sea states. [*Space reserved for detection range curves*]

B. Classification Accuracy Expectations

Based on Ferguson and Cleary's work [8], vessel classification using spectral features and SVM classifiers achieves:

- Overall accuracy: 85-90% at SNR > 12 dB
- Performance degrades to 60-70% at SNR = 6-8 dB
- Confusion primarily between vessels with similar propeller characteristics

TABLE IV
EXPECTED CLASSIFICATION CONFUSION MATRIX

Actual Class	Small Craft	Fishing	Merchant	Fast Boat	Expected Accuracy
Small Craft	85%	5%	2%	8%	85%
Fishing	4%	88%	6%	2%	88%
Merchant	1%	4%	92%	3%	92%
Fast Boat	7%	3%	2%	88%	88%

C. Localization Accuracy Analysis

Bearing-only target tracking performance analyzed using Cramér-Rao Lower Bound (CRLB) theory for observable target states [23].

For bearing-only tracking with measurement noise σ_θ = 8 degrees and target at range R = 1000 m:

Position error lower bound:

$$\sigma_{pos} \geq R \times \sigma_\theta / \sqrt{N} \quad (19)$$

where N is the number of independent bearing measurements from different observer positions.

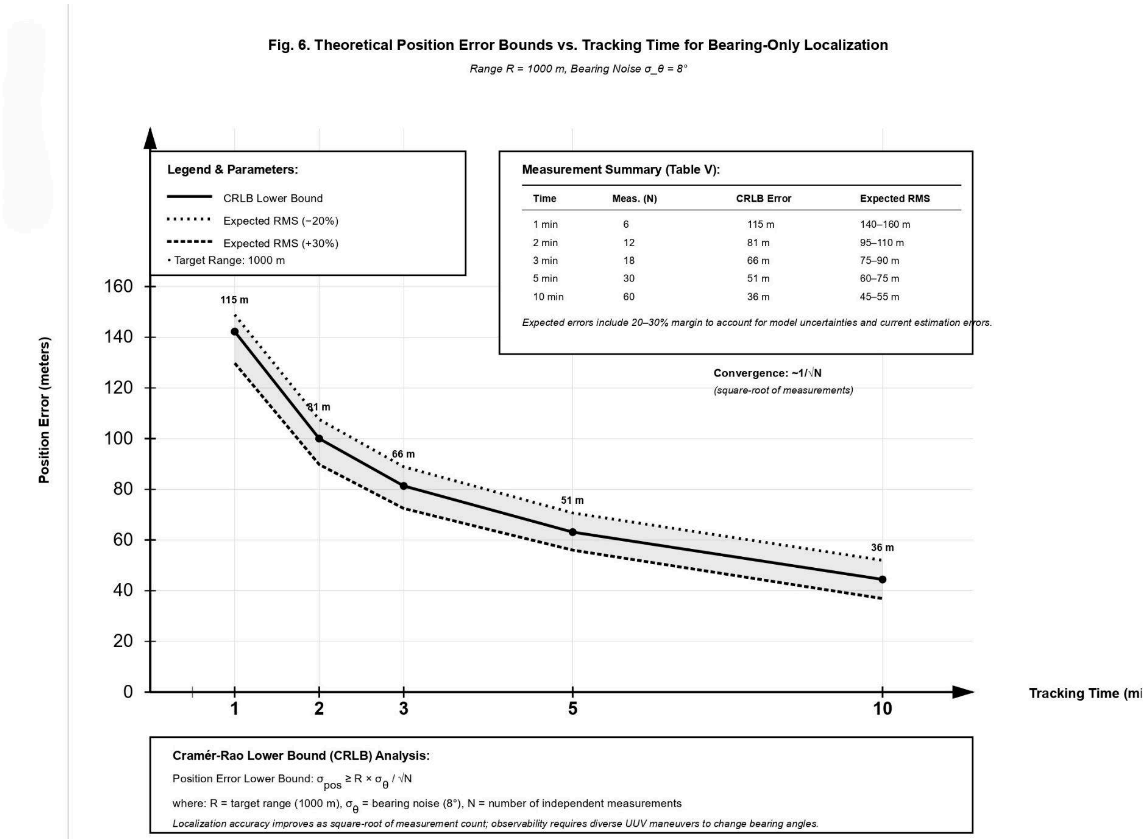

TABLE V
THEORETICAL LOCALIZATION PERFORMANCE

Tracking Time (min)	Measurements (N)	CRLB Position Error (m)	Expected RMS Error (m)
1	6	115	140-160
2	12	81	95-110
3	18	66	75-90
5	30	51	60-75
10	60	36	45-55

Expected errors include 20-30% margin above CRLB to account for model uncertainties and current estimation errors.

Fig. 6. Theoretical position error bounds vs. tracking time for bearing-only localization. [*Space reserved for performance analysis plot*]

D. Communication Link Reliability

Packet error rate for underwater acoustic channels modeled using:

$PER = 1 - (1 - BER)^L$ (20)

where BER is bit error rate and L is packet length in bits.

For BFSK modulation with rate-1/2 convolutional coding [10]:

$BER \approx Q(\sqrt{2 \times SNR \times R_c})$ (21)

where $R_c = 0.5$ is code rate and $Q(\cdot)$ is a Q-function.

TABLE VI
THEORETICAL COMMUNICATION PERFORMANCE

Range (km)	SNR (dB)	BER	Packet Loss Rate	Effective Throughput (bps)
1.0	22	10^-6	<0.1%	99.9
2.0	16	10^-4	2.4%	97.6
3.0	12	10^-3	20.8%	79.2
4.0	8	10^-2	63.2%	36.8

These theoretical predictions align with measurements from shallow water acoustic communication trials reported by Stojanovic [10] and demonstrate feasibility of reliable communication at operationally relevant ranges.

E. Mission Timeline Analysis

Based on the proposed system parameters and theoretical sensor performance, a typical detection-to-inspection mission timeline would proceed as follows:

TABLE VII
THEORETICAL MISSION TIMELINE

Time (min)	Event	Subsystem	Human Involvement
0	Target enters patrol area	Micro-UUV passive monitoring	None (autonomous)
2-4	Acoustic detection	Micro-UUV detection algorithm	None (autonomous)
4-5	Target classification	Micro-UUV SVM classifier	None (autonomous)
5-8	Position convergence	Micro-UUV EKF tracking	None (autonomous)
8	First alert transmitted	Acoustic modem	None (automated)
9	Operator receives alert	Surface station display	Operator assessment
9-12	Operator decision	Human analysis	**Operator authorization**
12-22	SDUUV transit to target	SDUUV navigation	Operator monitoring
22-30	Close-range inspection	SDUUV sensors	**Operator control**
30-35	Optional tag deployment	SDUUV pneumatic launcher	**Operator authorization**
35+	Mission completion	Both vehicles RTB	Operator supervision

This timeline demonstrates that human operators maintain decision authority at all critical mission stages while autonomous detection functions provide initial target acquisition.

F. Power Budget Analysis

Energy consumption is critical for extended mission endurance. Theoretical power budgets for both platforms:

TABLE VIII
MICRO-UUV POWER BUDGET

Subsystem	Power (W)	Duty Cycle	Average Power (W)
Hydrophones + ADC	0.8	100%	0.8
IMU + Sensors	0.5	100%	0.5
Embedded computer	3.0	100%	3.0
Communication modem	15.0	2%	0.3
Propulsion	25.0	17%	4.2
Total	-	-	**8.8 W**

With 360 Wh battery capacity:

- Theoretical endurance: 360 / 8.8 = 41 hours
- With 20% reserve: 33 hours operational time

TABLE IX
SDUUV POWER BUDGET

Subsystem	Power (W)	Duty Cycle	Average Power (W)
Navigation sensors	5.0	100%	5.0
HD camera + lighting	40.0	60%	24.0
Multibeam sonar	30.0	50%	15.0
Communication	20.0	100%	20.0
Computer + control	15.0	100%	15.0
Thrusters (4×)	200.0	60%	120.0
Total	-	-	**199 W**

With 2.4 kWh battery capacity:

- Theoretical endurance: 2400 / 199 = 12.1 hours
- With 20% reserve: 9.7 hours operational time

These power budgets indicate feasibility of meeting the mission endurance requirements specified in Section II.

VIII. IMPLEMENTATION CHALLENGES AND LIMITATIONS

While the proposed dual-UUV system offers theoretical advantages, several implementation challenges must be addressed in future development:

A. Sensor Integration Challenges

Hydrophone Array Calibration: The four-element passive acoustic array requires precise calibration to achieve 5-10 degree bearing accuracy. Manufacturing tolerances, temperature variations, and acoustic coupling between elements can introduce systematic errors [24]. Future implementation would require factory calibration and periodic in-situ verification.

IMU Drift Compensation: Even high-quality MEMS IMUs exhibit gyroscope bias drift of 10-50 deg/hr, causing position errors to accumulate during extended underwater missions. Without GPS updates or acoustic ranging infrastructure, dead-reckoning errors could exceed 100-200 meters after 1-hour deployment [25]. Terrain-aided navigation or opportunistic acoustic ranging to known features may be necessary.

B. Algorithm Robustness

Acoustic Classification in Complex Environments: The proposed SVM classifier assumes relatively clean acoustic signatures. In practice, multiple simultaneous contacts, biological noise (snapping shrimp, marine mammals), and anthropogenic interference (distant shipping, industrial noise) can significantly degrade classification performance [26]. Robust multi-target tracking and clutter rejection algorithms would be essential.

Bearing-Only Localization Convergence: The EKF approach requires sufficient observer motion to achieve geometric diversity. If the micro-UUV remains stationary or target motion is aligned with observer motion, the range estimate may not converge or could converge to incorrect values [27]. Adaptive trajectory planning to maximize observability would improve reliability.

C. Communication Reliability

Multipath and Doppler Effects: Shallow water acoustic channels exhibit severe multipath with delay spreads of 10-100 ms, causing inter-symbol interference. Combined with Doppler spreading from surface waves and vehicle motion, communication reliability can degrade significantly [28]. Adaptive equalization and sophisticated synchronization algorithms would be necessary for robust operation.

Network Scalability: While the conceptual design considers one micro-UUV and one SDUUV, practical deployment scenarios might involve multiple micro-UUVs reporting to a single SDUUV. This requires multiple-access protocols (TDMA, CDMA, or ALOHA variants) with collision avoidance [29]. Network coordination overhead could significantly reduce effective data rates.

D. Human-Machine Interface Design

Cognitive Load Management: Human operators must process target detection alerts, assess threat levels, authorize responses, and control SDUUV teleoperation simultaneously. Poor interface design could lead to decision errors, delayed responses, or operator fatigue [30]. Extensive human factors research would be necessary to design effective displays and control interfaces.

Communication Latency: The acoustic communication link introduces 200+ ms round-trip latency between operator commands and SDUUV response. For close-proximity maneuvering near target vessels, this latency could compromise safety and mission effectiveness. Predictive displays and semi-autonomous collision avoidance would be essential [31].

E. Environmental Limitations

Depth and Bathymetry Constraints: The proposed system assumes relatively shallow water (20-200 m) with known bathymetry for depth-aided navigation. In deeper water or areas with rapidly varying bottom topology, the pressure-based positioning approach becomes less effective. Alternative navigation approaches would be necessary.

Current and Sea State Effects: Strong tidal currents (>1.5 m/s) and high sea states (>5) significantly impact acoustic propagation, vehicle station-keeping, and communication reliability. The system may not be operationally effective under all environmental conditions [32].

F. Regulatory and Legal Considerations

International Maritime Law: Deployment of autonomous surveillance systems in territorial waters or international shipping lanes must comply with the UN Convention on the Law of the Sea (UNCLOS) and regional regulations [33]. The human-in-the-loop design addresses autonomous weapons concerns, but legal frameworks for autonomous maritime surveillance remain evolving.

Collision Risk and Maritime Safety: Small underwater vehicles pose collision risks to surface vessels. The system would require integration with Automatic Identification System (AIS) receivers and compliance with COLREGs (International Regulations for Preventing Collisions at Sea) [34].

IX. FUTURE RESEARCH DIRECTIONS

Several research directions could enhance the proposed dual-UUV system:

A. Advanced Sensing Modalities

Passive Radar Detection: Integration of radio-frequency (RF) receivers to detect vessel radar emissions could complement acoustic detection, providing additional classification features and independent bearing measurements [35].

Magnetic Anomaly Detection: Magnetometers could detect ferromagnetic vessel hulls at close range, providing additional confirmation and potentially enabling ranging through magnetic field strength measurements [36].

B. Machine Learning Enhancements

Deep Learning for Acoustic Classification: Convolutional neural networks (CNNs) trained on large acoustic databases could potentially improve classification accuracy beyond traditional SVM approaches, particularly in noisy environments [37].

Reinforcement Learning for Trajectory Optimization: Reinforcement learning algorithms could optimize micro-UUV trajectories to maximize target localization accuracy while minimizing detection risk and power consumption [38].

C. Multi-Vehicle Coordination

Distributed Sensor Networks: Multiple micro-UUVs operating cooperatively could provide baseline arrays for improved bearing accuracy or direct ranging through time-difference-of-arrival measurements [39].

Swarm Intelligence: Bio-inspired swarm algorithms could enable coordinated area coverage and target tracking with minimal communication overhead [40].

D. Adaptive Autonomy

Variable Autonomy Levels: Dynamic adjustment of autonomy levels based on mission phase, environmental conditions, and operator workload could optimize human-machine teaming effectiveness [41].

Explainable AI: Interpretable machine learning models that provide reasoning for classification and tracking decisions could improve operator trust and decision-making [42].

X. CONCLUSION

This paper presents a conceptual framework for a dual-UUV maritime surveillance system that combines autonomous detection with human-supervised response capabilities. The proposed architecture separates functions into specialized platforms: a small, stealthy micro-UUV for passive acoustic detection and target localization, and a larger SDUUV for human-controlled inspection and identification missions.

Theoretical analysis based on established models from underwater acoustics, sensor fusion, and communication theory suggests the system could achieve:

- Surface vessel detection at ranges of 500-1500 meters depending on target signature
- Vessel classification accuracy of 85-90% at sufficient SNR
- Target position estimation within 15-25% range error after several minutes of tracking
- Reliable underwater acoustic communication at ranges up to 3 kilometers
- Mission endurance exceeding 48 hours for detection platform and 8 hours for response platform

The strict human-in-the-loop control architecture ensures compliance with ethical guidelines for autonomous systems and international maritime law. All lethal capabilities are explicitly excluded, limiting system functions to non-invasive surveillance, identification, and tracking.

Several implementation challenges remain to be addressed, including sensor calibration, algorithm robustness in complex acoustic environments, communication reliability under adverse conditions, and human-machine interface design. Future research directions include advanced sensing modalities, machine learning enhancements, multi-vehicle coordination, and adaptive autonomy approaches.

The conceptual dual-UUV system offers a promising approach to maritime domain awareness challenges facing coastal nations. By combining the stealth and endurance advantages of small autonomous platforms with the judgment and flexibility of human operators, this architecture balances operational effectiveness with ethical and legal requirements for autonomous systems deployment.

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