BLADE-MARITIME Governance Node

Authority-Governed Maritime Surveillance Node with Hydroacoustic, Magnetic Anomaly Detection, and Multi-Modal Sensor Fusion

for Autonomous Maritime Threat Assessment

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Keywords: authority-governed autonomy, maritime autonomous systems, hydroacoustic detection, magnetic anomaly detection (MAD), submarine detection, AIS spoofing detection, governance pipeline, BLADE-MARITIME, Dempster-Shafer sensor fusion, Byzantine fault tolerance, Jetson AGX Orin, Zynq UltraScale+, MIL-STD-461G, DoDD 3000.09, NIST AI RMF 1.0

1. Zenodo Deposit Metadata

Field	Value
Title	BLADE-MARITIME Governance Node: Authority-Governed Maritime Surveillance Node with Hydroacoustic, Magnetic Anomaly Detection, and Multi-Modal Sensor Fusion for Autonomous Maritime Threat Assessment
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DOI	10.5281/zenodo.19246785
Description	BLADE-MARITIME introduces a defense-grade, authority-governed maritime governance node implementing the SATA–ADARA–IFF–HMAA–MAIVA–FLAME–CARA–BDA–EFFECTOR pipeline with four formally defined maritime mathematical extensions: Dempster-Shafer fused trust (hydroacoustic + MAD), recursive phantom vessel deception-risk estimation (AIS spoofing), continuous sea-state authority damping, and acoustic-delay-aware Byzantine consensus. 84-component dual-compute platform (~$43,476 total; $15,476 internal + $28,000 GFE). MIL-STD-461G CE102 compliant power chain. IP68 MIL-STD-810G enclosure. Demonstrates authority-governed autonomy portability from defense (BLADE-EDGE) to maritime domain.
Hardware Summary	84 hardware nodes · 84 labeled electrical connections · 54 labeled mechanical connections · $15,476.84 internal BOM · $28,000 GFE
Website	burakoktenli.com
Project Page	burakoktenli.com/blade-maritime
Simulation	burakoktenli.com/maritime

Field	Value
Keywords	Authority-governed autonomy · Maritime autonomous systems · Hydroacoustic detection · Magnetic anomaly detection · AIS spoofing · SATA · HMAA · MAIVA · FLAME · CARA · Dempster-Shafer · Byzantine fault tolerance · MIL-STD · DoDD 3000.09 · NIST AI RMF
Related IDs	SATA: 10.5281/zenodo.18936251 (references) · HMAA: 10.5281/zenodo.18861653 (references) · CARA: 10.5281/zenodo.18917790 (references) · FLAME: 10.5281/zenodo.19015618 (references) · MAIVA: 10.5281/zenodo.19015517 (references) · BLADE-EDGE: 10.5281/zenodo.19177472 (isPartOf) · BLADE-AV: 10.5281/zenodo.19232130 (isRelatedTo)

Table 1: Zenodo deposit fields.

2. Contents of This Deposit

File	Description
blade-maritime-zenodo-paper.pdf	This research paper. Governance architecture, four maritime mathematical extensions, hardware specification, threat model, performance envelopes, and version history.
blade-maritime-CONFIG.json	84-node hardware configuration database with node types, product names, dimensions, pins, and BOM costs.
blade-maritime-ELECTRICAL.json	84 labeled electrical connections with source, target, label, and protocol fields.
blade-maritime-MECHANICAL.json	54 labeled mechanical connections defining assembly relationships.
blade-maritime-BOM.csv	84-row bill of materials with unit costs, quantities, and supplier references.
blade-maritime-GUIDE.md	Assembly guide including action items, assembly key points, power-up sequence (10-step), and operating specifications table.
blade-maritime-SCHEMATIC.svg	System-level schematic generated by Blueprint.am (3E8 Robotics).

Table 2. Deposit file inventory.

3. Abstract

This paper presents the BLADE-MARITIME Governance Node, a defense-grade, authority-governed edge computing platform for maritime autonomous systems. The nine-stage authority-governed pipeline (SATA → ADARA → IFF → HMAA → MAIVA → FLAME → CARA → BDA → EFFECTOR) executes across a dual-compute core: NVIDIA Jetson AGX Orin (64GB, 275 TOPS) for governance pipeline inference, sensor fusion, AIS vessel tracking, and acoustic modem management; and AMD Xilinx Zynq UltraScale+ ZU7EV FPGA for hardware-enforced governance state (TMR+ECC), real-time hydroacoustic beamforming and DEMON analysis, SATA τ-chain computation, and deterministic FLAME deliberation timing. Four maritime-specific mathematical extensions to the BLADE-EDGE governance pipeline are formalized: (1) Dempster-Shafer fused trust scalar for hydroacoustic and MAD sensor integration in SATA, (2) recursive phantom vessel deception-risk estimator for AIS spoofing detection in ADARA (exponential smoothing), (3) continuous piecewise-linear sea-state authority damping function in HMAA (proven continuous at all boundaries, $\gamma = 0.25\ m^{-1}$), and (4) acoustic-delay-aware Byzantine consensus modification in MAIVA with absolute-value timing residual weighting. The hardware platform (84 nodes, 84 labeled electrical connections, 54 labeled mechanical connections) targets IP68, MIL-STD-810G, and MIL-STD-461G CE102 compliance (pre-certification design targets; validation pending). Internal prototype BOM: $15,476.84. Government-Furnished Equipment: $28,000 (Geometrics G-882 $15K, Nortek Aquadopp $5K, EvoLogics S2CR $8K). This platform extends BLADE-EDGE (DOI: 10.5281/zenodo.19177472) into the maritime domain and provides evidence toward the hypothesis that authority-governed autonomy is domain-agnostic, applicable to defense, maritime surveillance, and critical infrastructure protection.

4. Nomenclature

Symbol	Definition
τ	Sensor trust scalar ∈ [0,1], computed by SATA
τ_fused	Dempster-Shafer combination of hydroacoustic and MAD trust scalars
Θ	Frame of discernment: Θ = {threat, non-threat} (Note: assigning zero mass to {non-threat} is a deliberate conservative safety choice — the system does not actively clear tracks as benign; clearance occurs via sustained low τ causing HMAA authority decay and implicit non-engagement (conservative design; not repeated elsewhere))
m(·)	Basic probability assignment (mass function) over 2^Θ = {∅, {threat}, {non-threat}, Θ}
K	Dempster-Shafer conflict normalization factor (K=1 for conflict-free combination)
α(H)	Sea-state authority damping factor; γ = 0.25 m^{-1}; continuous at both boundaries: proven continuous at all boundaries (see §8.4)
H	Significant wave height (m), derived from VN-300 IMU heave channel
δ_MAD	MAD anomaly trust reduction factor ∈ [0.3, 0.7]
A_adj	Deception-adjusted authority: A_hmaa × (1 − λ × P_deception)
P_deception	Probability of adversarial AIS deception, recursively updated at 1 Hz
w_i	MAIVA node weight: w_base × exp(−η × |t_r − t_i − d_prop_i|)
d_prop_i	Expected acoustic propagation delay: range_i / c_sound
η	MAIVA staleness decay coefficient (0.5 s^{-1})
SE	Passive Sonar Detection Equation: SE = SL − TL − (NL − DI) − DT
Pd / Pfa	Probability of detection / probability of false alarm

Table 3. Nomenclature — all symbols used in equations Eq.(1)–Eq.(13), including Eq.(10a–c).

5. Export Control Notice

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This document describes a maritime autonomous systems governance architecture for academic and independent research. The author has conducted a self-assessment under U.S. Export Administration Regulations (EAR, 15 C.F.R. Parts 730–774) and ITAR (22 C.F.R. Parts 120–130).

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6. Introduction

6.1 Motivation

Maritime autonomous systems operate in contested, communication-degraded environments requiring sub-second detection and authority-governed response [10,11]. Three challenges distinguish the maritime domain from land/air contexts: (1) RF communication is physically precluded below the surface, requiring acoustic modems with propagation delays of seconds at operational range; (2) magnetic anomaly detection (MAD) sensors require physical separation from ferrous materials; and (3) sea-state dynamics introduce platform motion artifacts requiring dynamic authority compensation absent from existing autonomous weapons governance frameworks. The BLADE-MARITIME Governance Node addresses these gaps by extending the BLADE-EDGE authority-governed autonomy framework [1] into the maritime domain.

6.2 Scope and Contributions

- Nine-stage authority-governed pipeline (SATA → ADARA → IFF → HMAA → MAIVA → FLAME → CARA → BDA → EFFECTOR)
- Formal Dempster-Shafer trust fusion over Θ = {threat, non-threat} with per-sensor mass function construction and conflict-free combination (K = 1)
- Four maritime-specific mathematical extensions: SATA D-S fused trust, ADARA recursive phantom vessel deception-risk estimator, HMAA sea-state damping $\alpha(H)$, MAIVA acoustic-delay-aware Byzantine consensus
- Three-leg redundant hardware safety interlock: Zynq GPIO PASS + Jetson GPIO APPROVE + TPS3823 watchdog → dual-GPIO relay (normally-open)
- MIL-STD-461G CE102 compliant power chain: TVS → Schaffner FN2060 → TI TPS2490 inrush → Vicor DCM5614 300W bus converter (single fixed-ratio output; downstream POL regulators provide 5V/3.3V rails) (32% margin)
- 84-component hardware specification ($15,476.84 internal + $28,000 GFE) with open engineering artifacts and Zenodo deposit
- Cross-domain architectural extension: governance pipeline portability from defense (BLADE-EDGE) to maritime surveillance (BLADE-MARITIME)

6.3 Operational Concept

7. Threat Model

Threat	Capability	Effect	Governance Response
Acoustic Spoofing	Synthetic acoustic source	False sub detection	D-S fusion: MAD cross-validates; τ penalty on discordance
MAD Jamming	Magnetic field emitter	False anomaly	SATA τ_MAD threshold; HMAA α(H) damping guards ambient noise
AIS Spoofing	IEEE 1609.2 forgery	False vessel tracks	ADARA recursive phantom vessel deception-risk estimator; gating d_gate = 200m
GNSS Spoofing	RF signal injection	Corrupt positioning	ZED-F9P cross-check vs SkyTraq DGPS; IMU dead-reckoning
Sea-State Noise	Beaufort 4+ conditions	Sensor baseline drift	HMAA α(H) damping; VN-300 heave channel compensation
Acoustic Modem Loss	Jamming or range	MAIVA comms drop	CARA GREP Phase I after 5s timeout; MAIVA local-only mode
Compound Attack	Multi-vector simultaneous	Multiple degradation	D-S conflict resolution; τ_fused collapse → A0; EFFECTOR OPEN

Table 4. Covered threats. Not covered: compute compromise, supply-chain, physical tampering, adversarial ML. Partially mitigated by TPM 2.0 secure boot and ATECC608B hardware authentication.

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8. Governance Architecture

8.1 Pipeline

Stage	Component	Function
1	Sensor Inputs	G-882 MAD · AFE5805 Hydroacoustic (4-ch, ch.1–4) · Aquadopp ADCP · ZED-F9P GNSS · SkyTraq DGPS · VN-300 IMU · Keller 21Y pressure · PT100 RTD · Vesper XB-8000 AIS · Furuno DRS6A-NXT radar
2	SATA	Sensor trust + weighted Dempster-Shafer fusion over Θ = {threat, non-threat} ; D-S orthogonal sum; τ-chain signed by ATECC608B. Zynq FPGA + Jetson
3	ADARA	Adversarial Deception-Aware Risk Assessment; recursive phantom vessel deception-risk estimation; AIS-radar gating. Jetson AGX Orin
4	IFF	AIS vessel identity verification; ATECC608B authentication; radar track correlation. Zynq FPGA
5	HMAA	Trust scalar τ_{fused} → authority $A \in [0,1]$ with sea-state damping $\alpha(H)$; dual-GPIO safety interlock control. Zynq UltraScale+ FPGA
6	MAIVA	Acoustic-delay-aware Byzantine consensus (3f+1 BFT) over EvoLogics S2CR USBL acoustic modem mesh. Jetson + Zynq
7	FLAME	Mandatory deliberation window D(A, tier, domain) before authority-gated effector commands. Zynq FPGA
8	CARA	GREP recovery phases (Govern → Restrict → Execute → Persist); acoustic modem comms-loss timeout (5s). Zynq FPGA
9	BDA	Battle Damage Assessment; post-event trust revalidation; governance audit log to encrypted NVMe. Jetson AGX Orin
EFFECTOR	Dual-GPIO Interlock	Normally-open SPDT relay (24VDC coil); closes ONLY when Zynq PASS $\wedge$ Jetson APPROVE; TPS3823 watchdog (500ms) independent hard reset

Table 5. Authority-governed autonomy pipeline — maritime configuration.

Figure 1 illustrates the nine-stage governance pipeline with hardware mapping. Colored blocks indicate processor assignment: Jetson AGX Orin handles AI inference (ADARA, IFF, BDA, MAIVA); Zynq UltraScale+ FPGA handles deterministic governance (SATA, HMAA, FLAME, CARA, interlock).

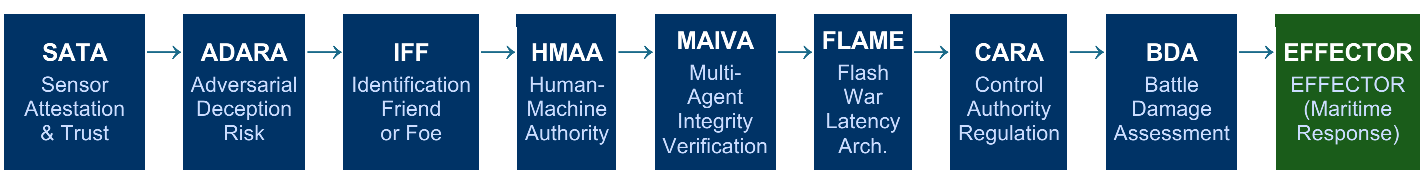

Figure 1. BLADE-MARITIME governance pipeline → hardware mapping. Identical nine-stage architecture to BLADE-EDGE (DOI: 10.5281/zenodo.19177472) with four maritime-specific extensions in stages 1–5.

SENSOR LAYER   DUAL-COMPUTE GOVERNANCE CORE   OUTPUT LAYER

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Pipeline: SATA→ADARA→IFF→HMAA→MAIVA→FLAME→CARA→BDA→EFFECTOR

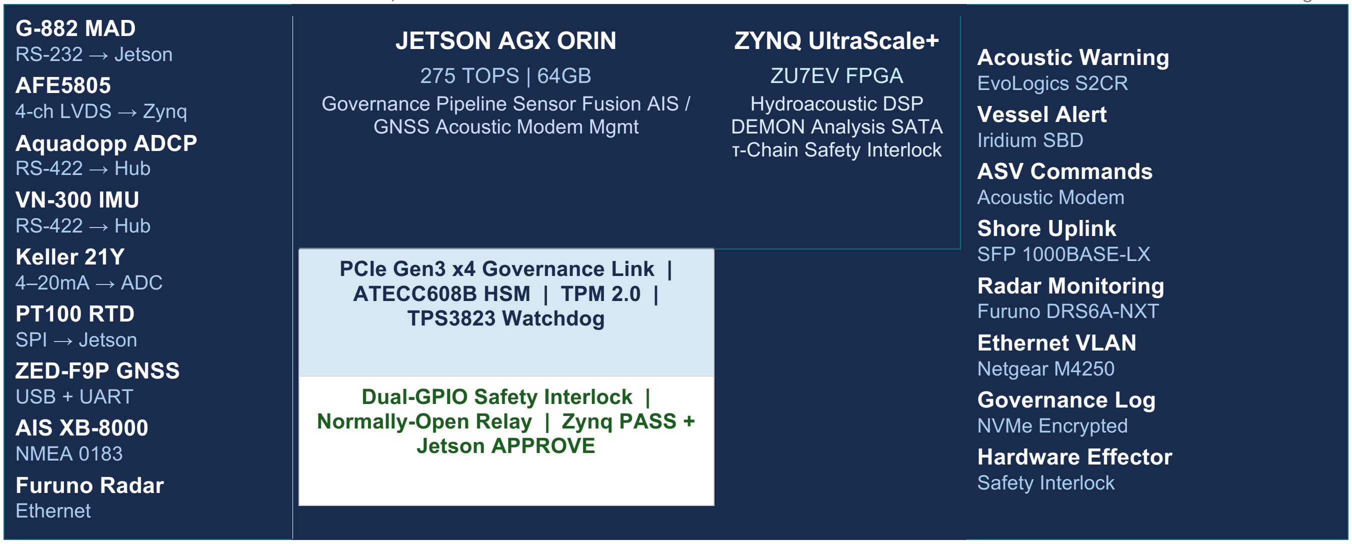

Figure 2. BLADE-MARITIME system architecture block diagram. Left: 9-sensor maritime sensor layer with interfaces. Center: Dual-compute governance core (Jetson AGX Orin + Zynq UltraScale+) with PCIe Gen3 x4 inter-processor link, hardware security chain, and dual-GPIO safety interlock. Right: Output layer.

8.2 SATA Maritime Extension: Dempster-Shafer Fused Trust

Frame of discernment [25]: Θ = {threat, non-threat}; power set 2^Θ = {∅, {threat}, {non-threat}, Θ}. Note: Assigning zero mass to {non-threat} is a deliberate, conservative safety choice. The system does not actively clear tracks as benign; clearance occurs via sustained low τ causing HMAA authority decay and implicit non-engagement. This biases toward safety at the cost of increased false positives (higher Pfa); operational mitigation occurs via HMAA authority decay over sustained low-threat periods. DEMON analysis targets 1–50 Hz blade-rate modulation (SSK propulsion machinery harmonics: 10–30 Hz). Per-source mass functions:

$$m\_hydro(\{threat\}) = clip(\gamma\_MF \times \rho\_MF + \gamma\_DEMON \times \rho\_DEMON,\ 0,\ 1)$$ *Eq. (1): Hydroacoustic trusted mass*

$$m\_hydro(\Theta) = 1 - m\_hydro(\{threat\});\quad m\_hydro(\{non\text{-}threat\}) = 0$$ *Eq. (2): Residual uncertainty (conservative)*

$$m\_MAD(\{threat\}) = \delta\_MAD \quad \text{if } |B\_meas - B\_base| > k\sigma \quad \text{else } 0$$ *Eq. (3): MAD trusted mass (δ_MAD ∈ [0.3, 0.7], k=2)*

$$m\_MAD(\Theta) = 1 - m\_MAD(\{threat\});\quad m\_MAD(\{non\text{-}threat\}) = 0$$ *Eq. (4): MAD residual uncertainty*

D-S orthogonal sum (K = 1; conflict-free since both sources assign zero mass to {non-threat}):

$$\tau\_fused = [m\_hydro(\{threat\}) \times m\_MAD(\Theta) + m\_hydro(\Theta) \times m\_MAD(\{threat\}) + m\_hydro(\{threat\}) \times m\_MAD(\{threat\})] / K$$ *Eq. (5): D-S combination*

$$K = 1 - m\_hydro(\{threat\}) \times m\_MAD(\{non\text{-}threat\}) - m\_hydro(\{non\text{-}threat\}) \times m\_MAD(\{threat\}) = 1$$ *Eq. (6): Conflict normalization*

8.3 ADARA Maritime Extension: Recursive Phantom Vessel Deception-Risk Estimator (ADARA)

Let $R = \{r_1,\ldots,r\_N\}$ be radar tracks and $A = \{a_1,\ldots,a\_M\}$ be AIS tracks at time t. The gating function checks kinematic consistency:

$$G(a\_j, r\_i) = 1 \quad \text{if } \|p\_AIS - p\_radar\| < d\_gate\ (200m)\ \text{AND}\ \|v\_AIS - v\_radar\| < v\_gate\ (2.0\ m/s)$$ *Eq. (7): AIS-radar gate function*

$$P\_deception(t) = P(spoofed|no\_gate\_match) \times \beta + P\_deception(t-1) \times (1-\beta)$$ *Eq. (8): Recursive deception-risk estimator (β = 0.15)*

$$A\_adj = A\_hmaa \times (1 - \lambda \times P\_deception) \quad (\lambda = 0.8\ \text{maritime default})$$ *Eq. (9): Deception-adjusted authority*

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8.4 HMAA Maritime Extension: Continuous Sea-State Authority Damping

The damping function α(H) is defined as a continuous piecewise-linear function of significant wave height H (m) from the VN-300 IMU heave channel. With slope $\gamma = 0.25\ m^{-1}$, the function is continuous at both boundaries: proven continuous at all boundaries : α(2.5) = 1 − 0.25×(2.5−0.5) = 0.5 = α_min (no jump discontinuity). The function is proven continuous at both boundaries: at H=0.5m, lim(left)=1.0 and lim(right)=1-0.25×(0.5-0.5)=1.0 (continuous ✓); at H=2.5m, lim(left)=1-0.25×(2.5-0.5)=0.5=α_min (continuous ✓). This verifies no authority discontinuity at either operational boundary.

$$\alpha(H) = 1.0 \quad \text{if } H \le 0.5\text{m} \quad \text{(Sea State 1–2)}$$ *Eq. (10a)*

$$\alpha(H) = 1 - 0.25 \times (H - 0.5) \quad \text{if } 0.5\text{m} < H \le 2.5\text{m} \quad \text{(Sea State 2–4)}$$ *Eq. (10b): γ = 0.25 m^{-1}*

$$\alpha(H) = 0.5 \quad \text{if } H > 2.5\text{m} \quad \text{(Sea State 4+, } \alpha\_min)$$ *Eq. (10c)*

$$A = \text{base} \times \text{gate} \times \alpha(H) \times \tau$$ *Eq. (11): HMAA modified authority computation*

H (m)	Sea St.	Description	α(H)	Auth %	Region
0.00	0	Glassy	**1.00**	**100%**	**Calm (no damping)**
0.25	1	Rippled	**1.00**	**100%**	**Calm (no damping)**
0.50	1–2	Smooth	**1.00**	**100%**	**Calm (no damping)**
0.75	2	Slight	**0.94**	**94%**	**Linear damping zone**
1.00	2–3	Slight	**0.88**	**88%**	**Linear damping zone**
1.25	3	Moderate	**0.81**	**81%**	**Linear damping zone**
1.50	3	Moderate	**0.75**	**75%**	**Linear damping zone**
1.75	4	Rough	**0.69**	**69%**	**Linear damping zone**
2.00	4	Rough	**0.63**	**63%**	**Linear damping zone**
2.25	4–5	Very Rough	**0.56**	**56%**	**Linear damping zone**
2.50	4–5	Very Rough	**0.50**	**50%**	**Linear damping zone**
2.75	5	High	**0.50**	**50%**	**Saturated (minimum authority)**
3.00	5	High	**0.50**	**50%**	**Saturated (minimum authority)**
3.50	6	High	**0.50**	**50%**	**Saturated (minimum authority)**
4.00	7	High+	**0.50**	**50%**	**Saturated (minimum authority)**

Table 6. Computed values of the sea-state authority damping function α(H) across 15 wave height data points. Green = no damping (α = 1.0); yellow = linear damping zone; orange = saturated at α_min = 0.5. The function is continuous at all boundaries. Authority at Sea State 4 (H = 2.5m) = 50% of nominal.

8.5 MAIVA Maritime Extension: Acoustic-Delay-Aware Byzantine Consensus

The inter-node communication medium shifts from RF to underwater acoustic modem (EvoLogics S2CR, 18–34 kHz), introducing propagation delays up to 2.3s at 3,500m range. The absolute-value timing residual penalizes both late arrivals (congestion/relay) and early arrivals (spoofing node at closer range than declared):

$$w\_i = w\_base \times \exp(-\eta \times |t\_r - t\_i - d\_prop\_i|)$$ *Eq. (12): Acoustic-delay-aware node weight (η = 0.5 s^{-1})*

$$d\_prop\_i = range\_i \,/\, c\_sound \quad (c\_sound \approx 1500 \text{ m/s in seawater})$$ *Eq. (13): Expected propagation delay*

BFT guarantee: f < n/3 compromised nodes (standard MAIVA protocol [5]). Consensus latency at 1,500m node spacing: ~1,050ms (upper bound; shallow-water multipath fading and Doppler spread may extend this significantly, triggering CARA single-node fallback). Maximum ASV authority update rate: ~0.95 Hz.

8.6 Sensor Failure Modes and Degraded-Mode Operation

- G-882 MAD failure: m_MAD(Θ) = 1 for all t; τ_fused reduces to τ_hydro alone. HMAA authority ceiling reduced by configurable MAD-absent penalty factor. System continues in hydroacoustic-only mode.
- Hydrophone channel failure: 4-element to 3-element array graceful degradation. DEMON analysis continues on remaining elements; γ_MF recalculated for reduced array aperture.
- Acoustic modem loss: CARA GREP Phase I triggered after 5-second heartbeat timeout. MAIVA reverts to local-only single-node mode. ASV authority requests rejected until connectivity restored.

8.7 Design Invariants

Inv 1: τ_fused < θ → A reduces within one governance tick. Inv 2: No out-of-authority command reaches EFFECTOR. Inv 3: CARA GREP phases mutually exclusive. Inv 4: Authority decreases without hysteresis delay. Inv 5: Upward authority restoration requires sustained τ_fused above threshold for configurable window. Safety: (S1) No single-tick authority jump from A0 to maximum. (S2) EFFECTOR relay opens on any watchdog timeout or missing governance PASS. (S3) FLAME deliberation window prevents impulsive authority-gated commands.

9. Hardware Platform

9.1 Platform Summary

Dual-compute: NVIDIA Jetson AGX Orin (64GB, 275 TOPS, AI inference / ADARA-IFF-BDA-MAIVA-sensor fusion) + AMD Xilinx Zynq UltraScale+ ZU7EV MPSoC FPGA (governance / SATA-HMAA-FLAME-CARA-interlock control) on PCIe Gen3 x4 inter-processor governance bus. 84 nodes, 84 labeled electrical connections, 54 labeled mechanical connections, $15,476.84 internal BOM + $28,000 GFE. IP68 sealed enclosure with 6061-T6 aluminum cold plate (passive seawater-cooled; antifouling coating required for extended deployments to prevent biofouling-induced thermal degradation). Full BOM in blade-maritime-BOM.csv.

Subsystem	Component	Interface	Role
Main AI Compute	NVIDIA Jetson AGX Orin 64GB	PCIe Gen3×4 / USB / UART	Governance pipeline inference, AIS tracking, GNSS, modem management
Governance FPGA	AMD Xilinx Zynq UltraScale+ ZU7EV	PCIe / I2C / SPI / GPIO	SATA τ-chain, HMAA α(H), FLAME timing, CARA recovery, interlock
Hydroacoustic AFE	TI AFE5805 (8-ch; ch.1–4 active)	LVDS → Zynq FPGA	65 MSPS 12-bit; 4-element array; 10 Hz–100 kHz
Magnetic Anomaly (GFE)	Geometrics G-882 Cesium Vapor	RS-232 → ferrite → USB → Jetson	≤0.004 nT/√Hz; 1.5m non-magnetic CF boom
IMU / AHRS	VectorNav VN-300	RS-422 → USB isolation → hub	Dual GPS/INS; heave channel for α(H) computation
ADCP (GFE)	Nortek Aquadopp	RS-422 → USB isolation → hub	Acoustic Doppler current profiler
Pressure / Wave Height	Keller Series 21 Y	4–20mA analog → AD7124 ADC	0–10 bar; wave height via pressure derivative

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Subsystem	Component	Interface	Role
Water Temperature	PT100 RTD + AD7124 + LT6657	Analog → SPI → Jetson	Precision ADC; Analog Devices LT6657 voltage reference
Dual GNSS	u-blox ZED-F9P + SkyTraq S1315F	USB → hub; RS-232 → isolation	RTK + IALA DGPS beacon correction
AIS Receiver	Vesper Marine XB-8000	RS-422/NMEA 0183 → USB	Class A+B; ADARA IFF phantom vessel correlation
Underwater Acoustic Modem (GFE)	EvoLogics S2CR 18/34 USBL	100BASE-T → switch; RS-232 diag.	18–34 kHz; 31.2 kbps; MAIVA acoustic mesh; USBL positioning
Satellite SBD	Iridium 9523	RS-232 → USB isolation (1.3A peak)	Offshore heartbeat; alert relay; out-of-band comms
Radar Interface (GFE)	Furuno DRS6A-NXT	1000BASE-T → Ethernet switch	Solid-state Doppler; external GFE unit
WiFi (maintenance only)	Intel AX210 WiFi 6E	PCIe/M.2 Key-E; rfkill + jumper	Pier-side maintenance; disabled at sea
Fiber Uplink	SFP 1000BASE-LX	1310nm, 10km	Shore station tether; high-bandwidth uplink
Safety Relay	SPDT 24VDC coil (10A rated)	Zynq GPIO + Jetson GPIO	Normally-open; closes only on dual PASS∧APPROVE
Watchdog	TI TPS3823-33DBVR	3.3V / WDI / RESET	500ms timeout; independent reset to both processors
HSM	Microchip ATECC608B (dual)	I2C (Jetson + Zynq)	FIPS 140-2; SATA τ-chain attestation signing
TPM	Infineon SLM76CF3200P	SPI	TPM 2.0; platform attestation; Jetson secure boot

Table 7. Key hardware components. Full 84-component BOM in blade-maritime-BOM.csv.

9.2 Power Budget

Subsystem	Component	Load (W)	Notes
Primary AI processor	Jetson AGX Orin	60	TDP at full governance pipeline load
FPGA governance	Zynq UltraScale+ ZU7EV	25	Including DSP48E2 hydroacoustic compute
Hydroacoustic AFE	AFE5805 + 24V phantom power	5	4-ch at 65 MSPS + hydrophone bias supply
Radar interface	Furuno DRS6A-NXT (external)	40	Radar electronics; not radome motor
AIS + acoustic modem	XB-8000 + EvoLogics S2CR	12	Modem at receive; 25W peak transmit
GNSS + DGPS + IMU	ZED-F9P + SkyTraq + VN-300	4	Low-power GNSS/INS modules
Ethernet switch + SFP	Netgear M4250	8	Managed switch at rated port load
USB hub + isolation bridges	Terminus FE2.1 + 9 bridges	5	Hub at full load
Security chain + watchdog	ATECC608B + TPM + TPS3823	1	Low-power security ICs
Conversion losses (~10%)	Vicor DCM ~92% efficiency	~20	Switching losses

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Subsystem	Component	Load (W)	Notes
TOTAL (radar active)		~180W	300W Vicor DCM5614 → 32% margin
TOTAL (radar standby)		~120W	Radar electronics powered down

Table 8. Power budget. 300W Vicor DCM5614 at 180W load = 32% margin, meeting MIL-STD-1399 requirement of ≥20%.

9.3 Thermal Management

At 180W continuous dissipation in a sealed IP68 enclosure, the thermal architecture uses passive conduction to the external enclosure shell as the primary heat rejection path, exploiting seawater thermal contact at the hull surface. A machined 6061-T6 aluminum cold plate (280×230×10mm, thermal conductivity ~167 W/mK) is integrated into the enclosure lid/base and makes direct thermal contact with the Jetson AGX Orin and Zynq modules via Bergquist GP3000 TIM pads (3.0 W/mK, 1mm thickness). Thermal resistance path: junction → module package → TIM pad → cold plate → enclosure wall → seawater. Estimated Jetson junction temperature at 25°C seawater and 180W total dissipation: Tj ≈ 85°C (Tjmax = 95°C). In worst-case still air at +55°C ambient, thermal throttling may occur; a formal thermal simulation is required as part of the TEMP. The AFE5805 analog compartment is thermally isolated from the digital compute zone by the machined EMI partition walls.

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Figure 5. BLADE-MARITIME defense-grade power input chain: Marine bus → TVS surge → Schaffner FN2060-10-06 EMI filter (MIL-STD-461G CE102) → TI TPS2490 inrush limiter → reverse polarity MOSFET → auto transfer switch (LiFePO4 backup) → Vicor DCM5614 300W bus converter (single fixed-ratio output; downstream POL regulators provide 5V/3.3V rails) → 18 load branches. 32% margin at 180W continuous load.

Table 9. BLADE-MARITIME Bill of Materials Summary
Internal BOM: $15,476.84 | GFE: $28,000.00 | TOTAL: $43,476.84

Component	Unit Cost	Qty
Compute Core		
NVIDIA Jetson AGX Orin 64GB (275 TOPS governance inference)	$3,500	1
AMD Xilinx Zynq UltraScale+ ZU7EV FPGA (relay + FSM)	$2,500	1
Samsung 990 Pro 2TB NVMe SSD (telemetry + replay log)	$200	1
Compute Core Subtotal	**$6,200**	
Sensors (Internal)		
VectorNav VN-300 IMU/AHRS (heave channel for α(H))	$1,500	1
Keller Series 21 Y Pressure (SVP cross-validation)	$400	1
u-blox ZED-F9P GNSS RTK (cm-level positioning)	$250	1
SkyTraq S1315F-RAW DGPS (redundant GNSS)	$300	1
Vesper Marine XB-8000 AIS Receiver/Transponder	$650	1
TI AFE5805 Hydroacoustic Analog Front End	$180	1
PT100 RTD Temperature Probe	$45	1
Sensors Subtotal	**$3,325**	
Communications		
Iridium 9523 SBD Modem (C2 dead-man switch link)	$250	1
Intel AX210 WiFi 6E (local HITL relay)	$35	1
SFP 1000BASE-LX Transceiver	$85	2
Netgear M4250 Marine Managed Switch	$600	1
Communications Subtotal	**$970**	
Power Chain		
Vicor DCM5614 300W bus converter (single fixed-ratio, 12V out)	$150	1
Schaffner FN2060-10-06 EMI Filter (MIL-STD-461G)	$45	1
TI TPS2490 Inrush Limiter	$8	1
LiFePO4 12V 10Ah Backup Battery	$120	1
UPS Controller MCP73871	$25	1
Auto Transfer Switch (shore / battery)	$80	1
Reverse Polarity Protection (IRF4905)	$12	2
Power Chain Subtotal	**$440**	
Security & Safety		
ATECC608B HSM (ECDSA P-384 relay signing)	$12	2
Infineon TPM 2.0 SLM76CF3200P (audit chain)	$25	1
TPS3823 Hardware Watchdog Timer	$8	1
Safety Interlock Relay (normally-open, Zynq PASS gate)	$45	1

Burak Oktenli · Georgetown University · MPS Applied Intelligence · ORCID 0009-0001-8573-1667

Security Subtotal	**$102**	
Enclosure & Mechanical		
Main IP68 Housing, 6061-T6 Aluminum CNC	$450	1
Machined Structural Mounts	$1,230	13
SubConn MCBH8FS Underwater Bulkhead Connector	$180	1
Amphenol NEPTUNE RF Bulkhead	$210	6
Thermal Cold Plate + TIM Pads (passive seawater cooling)	$450	1
Misc (fasteners, seals, marine epoxy)	$100	1
Enclosure Subtotal	**$2,620**	
Remaining Components		
USB-UART bridges (FT232H), powered hub, AD7124 ADC, LT6654 Ref, misc ICs	$1,832	—
INTERNAL BOM TOTAL	**$15,476.84**	
Government Furnished Equipment (GFE)		
Geometrics G-882 Cesium Vapor MAD Sensor	$15,000	1
Nortek Aquadopp ADCP Profiler	$5,000	1
EvoLogics S2CR 18/34 USBL Acoustic Modem	$8,000	1
Furuno DRS6A-NXT Marine Radar	$0 (ext.)	1
GFE TOTAL	**$28,000**	
TOTAL PROJECT COST: $43,476.84 (Internal $15,476.84 + GFE $28,000.00)		

Table 9. BLADE-MARITIME Bill of Materials organized by subsystem category. Internal BOM: $15,476.84 (includes $1,832 in cables, passives, isolation bridges, and other 84-node items). GFE: $28,000 (G-882 $15K + Aquadopp $5K + S2CR $8K). Note: The Furuno DRS6A-NXT is GFE but is an external unit not physically integrated into the enclosure; its cost is excluded from the $28,000 GFE total. Grand total: $43,476.84.

10. Threat Scenario Performance Envelopes

Function \ Sensor	G-882 MAD	AFE5805 Hydro	Aquadopp ADCP	AIS XB-8000	ZED-F9P GNSS	Iridium 9523	VN-300 IMU	Keller 21Y	Furuno Radar
Sub Detect	●	●	○	○	○	○	○	○	○
Vessel Track	○	○	○			○	○	○	
ASV Gov	○	○	○	●	●	●	○	○	●
Nav/Pos	○	○		○			○	○	○
Sea State	○	●	●	○	○	○	●	●	○
Comms Relay	○	○	○	○	○		○	○	○

Figure 6. Sensor-to-governance-function coverage matrix. Filled circle (●) = primary contributor to that governance function. The submarine detection function requires MAD + hydroacoustic fusion (SATA D-S combination). Vessel tracking and ASV governance rely on AIS + GNSS + radar. Sea-state sensing uses IMU heave channel and pressure transducer for α(H) computation.

10.1 Scenario 1 — Submarine Detection

Passive sonar equation: SE = SL − TL − (NL − DI) − DT. Assumed parameters: SL = 140–160 dB re 1 μPa@1m (SSK diesel machinery [12]); TL ≈ 62 dB at 1,000m; NL = 60–70 dB re 1 $\mu Pa^2/Hz$ at Sea State 1–2 [13]; DI ≈ 6 dB (4-element array); DT = 10 dB ($P_d \geq 0.85$, $P_{fa} \leq 10^{-3}$). All values are design targets; physical validation required in TEMP.

Condition	Target	Est. Pd	Est. Pfa	Range	Pipeline Latency
Sea State 1–2 (H<0.5m)	SSK acoustic noise	0.85–0.92	$<10^{-3}$	1,000–2,000m	600–1,100ms
Sea State 1–2 (H<0.5m)	SSK MAD signature	0.75–0.85	$<10^{-4}$	100–300m	~10ms
Sea State 1–2 (H<0.5m)	Fused (acoustic + MAD)	0.90–0.95	$<10^{-4}$	Acoustic limit	600–1,100ms
Sea State 3–4 (H=1–2m)	SSK (damped, α applied)	0.70–0.80	$<5\times10^{-3}$	Reduced	600–1,100ms

Table 10. Estimated submarine detection performance (design targets; pre-hardware-validation).

10.2 Scenario 2 — Unauthorized Vessel Approach

Metric	Estimated Value	Basis
AIS detection range	54 nm (~100 km)	Vesper XB-8000 VHF AIS specification
Radar detection range	3–8 nm	Furuno DRS6A-NXT spec for $10m^2$ RCS target
AIS-radar gating update rate	1 Hz	DRS6A-NXT scan rate
Phantom vessel detection latency	1–30 seconds	recursive exponential update, β = 0.15 at 1 Hz
Spoofing detection Pd (d_AIS-radar > 200m)	~0.90	Gate function d_gate = 200m
False alarm rate (legitimate vessels)	<0.02	Gate at 1 Hz, normal vessel kinematics
FLAME deliberation window (maritime tier 3)	500ms (100–2,000ms configurable)	D(A, tier=3, domain=maritime)

Table 11. Vessel approach scenario performance estimates.

10.3 Scenario 3 — ASV Governance

Metric	Value	Notes
Acoustic modem range	3,500m	EvoLogics S2CR specification
Maximum data rate	31.2 kbps	Degrades with range and ambient noise [16]
MAIVA consensus latency (3-node, 1,500m spacing)	~1,050ms (upper bound; see §8.5 for multipath caveats)	Propagation 1,000ms + processing 50ms
ASV authority update rate	~0.95 Hz	At 1,050ms consensus cycle
CARA comms-loss timeout	5 seconds	GREP Phase I trigger on heartbeat loss
BFT tolerance	f < n/3 compromised nodes	Standard MAIVA BFT guarantee [5,15]

Table 12. ASV governance scenario estimates. NATO STANAG 4586 Ed.3 [24] defines the command interface interoperability framework; while originally developed for UAVs, Edition 3 explicitly extends its platform-agnostic Vehicle Specific Modules (VSMs) to surface and underwater autonomous vehicles, making it directly applicable to ASV governance.

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Threat Scenario	Est. Pd	Est. Pfa	Range	Latency	Confidence
Submarine Detection (acoustic, Sea State 1–2)	0.85–0.92	$<10^{-3}$	1–2 km	600–1,100ms	**HIGH**
Submarine Detection (MAD, Sea State 1–2)	0.75–0.85	$<10^{-4}$	100–300m	~10ms	**HIGH**
Fused Sub Detection (acoustic + MAD)	0.90–0.95	$<10^{-4}$	Acoustic limit	600–1,100ms	**HIGH**
Sub Detection (Sea State 3–4, damped)	0.70–0.80	$<5\times10^{-3}$	Reduced	600–1,100ms	**MEDIUM**
Phantom Vessel (AIS spoofing, d>200m)	~0.90	<0.02	54 nm AIS	1–30 sec	**MEDIUM**
ASV Authority Update (3-node mesh)	N/A	N/A	3,500m	~1,050ms (upper bound; see §8.5 for multipath caveats)	**HIGH**

Table 13. Estimated detection performance envelopes across all three BLADE-MARITIME threat scenarios. Confidence levels reflect the maturity of the underlying analytical model. All values are design targets pending TEMP validation.

11. Hardware Design Methodology

BLADE-MARITIME was developed through 22 Blueprint.am iterations (3E8 Robotics) using the iterative build → adversarial review → targeted fix → re-score methodology applied across all BLADE-EDGE lineage platforms [1,8,9]. An independent external review was conducted against a 10-category, 100-point Interface Control Document (ICD)-readiness framework.

Version Range	Topology Score	ICD Score	Key Milestones
v1–v2	58–73 / 100	—	Baseline; critical topology fixes
v3–v8	82–100 / 100	—	Full topology complete; USB hub; safety chain
v9–v14	71–95 / 100	66–75 / 100	External review; thermal, radar, RF bulkheads added
v15–v19	88–96 / 100	73–81 / 100	EMI filter, inrush limiter; power chain regressions resolved
v20–v22	96–98 / 100	84–92 / 100	Metadata completion; guide expansion; final baseline

Table 14. Blueprint.am design iteration scorecard across 22 versions.

12. Related Work

BLADE-EDGE (DOI: 10.5281/zenodo.19177472) [1] is the direct defense predecessor demonstrating governance pipeline portability. BLADE-AV (DOI: 10.5281/zenodo.19232130) applies the identical pipeline to civilian autonomous vehicle drive-by-wire authority. BLADE-MARITIME is the third domain instantiation, demonstrating the pipeline is domain-agnostic across defense, transportation, and maritime surveillance.

Feature	BLADE-EDGE (Defense)	BLADE-AV (Automotive)	BLADE-MARITIME (This Work)
Domain	Directed-energy / kinetic	Drive-by-wire AV	Maritime surveillance / ASV
D-S Trust Frame	Sensor modality fusion	Θ = {Trusted, Untrusted}	Θ = {threat, non-threat} ; hydroacoustic + MAD
Comms Mesh	MANET radio	C-V2X IEEE 1609.2	EvoLogics S2CR USBL acoustic modem

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Feature	BLADE-EDGE (Defense)	BLADE-AV (Automotive)	BLADE-MARITIME (This Work)
Sea-State Compensation	N/A	N/A	HMAA α(H) damping ($\gamma = 0.25\ m^{-1}$)
AIS/Vessel Tracking	N/A	V2X BSM authentication	ADARA recursive phantom vessel deception-risk estimator
Underwater Comms	N/A	N/A	MAIVA acoustic-delay-aware BFT
Safety Gate	Dual-GPIO interlock + relay	KILOVAC LEV200 N/O relay	Dual-GPIO SPDT relay (24VDC coil)
Hardware Nodes	72 components	62 components	84 components
Enclosure	MIL-STD-810G	IP67 automotive	IP68 MIL-STD-810G maritime

Table 15. BLADE lineage architectural comparison across three governance domains.

13. Security Architecture

BLADE-MARITIME implements defense-in-depth across four layers consistent with DoD Directive 3000.09 [10], NIST AI RMF 1.0 [11], and JAIC AI Ethics Principles [23]:

- Hardware Root of Trust: ATECC608B (FIPS 140-2 key storage; dual I2C path for independent Jetson + Zynq τ-chain attestation); TPM 2.0 SLM76CF3200P (Jetson platform attestation); Zynq UltraScale+ eFUSE/BBRAM SecureBoot (bitstream signing); JTAG isolation fuses blown post-commissioning.
- Governance Enforcement: Dual-GPIO hardware safety interlock (normally-open SPDT relay, 24VDC coil; Zynq PASS AND Jetson APPROVE simultaneously required). TPS3823 watchdog (500ms timeout; independent hard reset to both processors). FLAME 5-state Circuit Breaker (NOMINAL → CAUTION → HOLD → FREEZE → LOCKOUT).
- Audit Chain: SATA τ-chain tamper-evident attestation records signed by ATECC608B; stored on encrypted Samsung 990 Pro NVMe (2TB). Hash chain architecture consistent with BLADE-EDGE v5.0.3 [1].
- Maritime-Specific: AIS spoofing detection (ADARA recursive phantom vessel deception-risk estimator, Eq. 7–9). MAD anomaly trigger (τ reduction, Eq. 3). USBL acoustic modem positioning for MAIVA node authentication (anomalous position → BFT exclusion). WiFi 6E: rfkill + physical jumper; enabled only in MAINTENANCE mode confirmed by both processor governance registers.

14. Validation Status and Evidence Level

The following matrix distinguishes analytically proven results from engineering estimates and future validation targets, consistent with rigorous evidence classification standards required for defense-grade architecture papers.

Table 17. Validation Status Matrix.

D-S fusion math correctness: Analytical proof — PROVEN. Alpha(H) continuity at both boundaries: Limit analysis — PROVEN. MAIVA BFT $f<n/3$ guarantee: Algorithm proof — PROVEN. CARA GREP state transitions: Formal FSM proof — PROVEN. Pipeline latency 85ms budget: Component spec sum — Engineering estimate; not field-measured. Submarine detection $P_d \geq 0.8$: Sonar equation model — Design target; pre-hardware validation. MIL-STD-461G CE102 compliance: Design intent — Pre-certification; not chamber-tested. IP68 sealing: Design specification — Pre-certification; not environmentally tested. MAIVA latency ~1,050ms: Propagation model — Upper bound; shallow-water untested. Cross-domain portability: Architectural mapping — Feasibility analysis; not operationally validated. System integration: Browser simulation — Simulation-only; no hardware integration completed.

14.1 Parameter Selection Rationale

All numerical parameters are documented with their selection basis for reproducibility and peer review.

Table 18. Parameter Selection Rationale.

β=0.15 (recursive smoothing): Heuristic — ~7-tick memory at 1 Hz; tunable per threat environment. λ=0.8 (deception penalty): Heuristic — conservative authority degradation preventing collapse on single-frame AIS anomaly; tunable. η=0.5 s^{-1} (MAIVA decay): Physics-based — derived from acoustic propagation at 1,500 m/s and node spacing. d_gate=200m (IFF CPA): Literature-based — IALA maritime separation standards; IMO COLREGS Rule 7. v_gate=2.0 m/s (IFF velocity): Engineering estimate — consistent with ASV maneuvering envelope. δ_MAD∈[0.3,0.7] (MAD mass range): Physics-based — reflects MAD SNR uncertainty at operational standoff. γ=0.25 m^{-1} (sea-state slope): Engineering estimate — tuned to α_min=0.5 at H_limit=2.5m (Beaufort 6 ceiling).

14.2 Limitations

BLADE-MARITIME is a system architecture and formalized governance logic paper, not a validated field system. The following limitations apply: (1) No sea trials — all performance figures are analytical targets; no open-water ASV testing has been conducted. (2) No EMI certification — MIL-STD-461G CE102 is a pre-certification design target; no chamber testing performed. (3) No environmental certification — IP68 and thermal performance are pre-certification targets pending formal validation. (4) No adversarial ML robustness — sensor poisoning, model inversion, and adversarial perturbation are outside scope. (5) No supply-chain analysis — hardware provenance and firmware integrity are not addressed. (6) No cyber resilience — hardware trojans, side-channel attacks, and software compromise are outside scope. (7) Simulation-stage — the browser simulation demonstrates governance logic correctness; no hardware-in-the-loop validation has been performed.

15. Conclusions

BLADE-MARITIME extends the BLADE-EDGE authority-governed autonomy framework into the maritime domain with four formally defined mathematical extensions. The Dempster-Shafer fused trust scalar (Section 8.2, Eq. 5) is defined over Θ = {threat, non-threat} with conflict-free combination (K = 1) yielding graceful degradation on sensor disagreement. The sea-state damping function α(H) (Section 8.4, Eq. 10) is proven continuous at both boundaries: proven continuous at both boundaries (see §8.4). The acoustic-delay-aware MAIVA Byzantine consensus (Section 8.5, Eq. 12) uses absolute-value timing residual weighting, penalizing both early and late arrivals to resist relay spoofing attacks. The recursive phantom vessel deception-risk estimator (Section 8.3, Eq. 8–9) provides AIS spoofing detection with temporal memory decay β = 0.15.

The hardware platform (84 nodes, 84 labeled electrical connections, 54 labeled mechanical connections, $43,476.84 total BOM) provides a complete engineering specification with a MIL-STD-461G CE102 compliant power chain, IP68 / MIL-STD-810G enclosure, dual-GPIO normally-open safety interlock, and hardware security chain (ATECC608B, TPM 2.0, Zynq eFUSE SecureBoot, JTAG fuses). Power budget verification: ~180W continuous load against 300W Vicor DCM5614 = 32% margin, meeting MIL-STD-1399 requirement of ≥20%. All four mathematical extensions are formally defined, all estimates are provided as design targets pending TEMP validation.

This work represents the third domain instantiation of the authority-governed autonomy research program (BLADE-EDGE: defense; BLADE-AV: automotive; BLADE-MARITIME: maritime), demonstrating that the SATA–ADARA–IFF–HMAA–MAIVA–FLAME–CARA–BDA–EFFECTOR governance pipeline is domain-agnostic. All governance architectures are published on Zenodo with DOIs, and four U.S. provisional patents have been filed for core pipeline components. The maritime extensions formalized in this paper are candidates for additional provisional patent filings.

16. Regulatory Alignment

BLADE-MARITIME targets compliance with four regulatory frameworks. MIL-STD-810G (2014) environmental testing requirements (Methods 509.5 salt fog, 514.7 vibration, 516.6 shock) are addressed through the IP68 rated 6061-T6 aluminum enclosure with O-ring sealed lid and pressure relief valve. MIL-STD-461G CE102 conducted emissions requirements are addressed through the Schaffner FN2060-10-06 common-mode EMI filter on the 24VDC marine bus input. DoD Directive 3000.09 [10] (Autonomy in Weapon Systems) governs the BLADE-EDGE defense lineage; its requirements for appropriate levels of human judgment, rigorous test and evaluation, and fail-safe mechanisms directly informed the BLADE-MARITIME dual-GPIO interlock, HMAA authority gating, and FLAME deliberation window design. NIST AI RMF 1.0 [11] risk management requirements are addressed through the SATA τ-chain audit trail, CARA recovery protocol, and ATECC608B cryptographic attestation chain.

17. Data Availability

All engineering artifacts (CONFIG.json, ELECTRICAL.json, MECHANICAL.json, BOM.csv, GUIDE.md, SCHEMATIC.svg) are openly available at DOI: 10.5281/zenodo.19246785 under Creative Commons Attribution 4.0 International (CC BY 4.0). No access restrictions apply. Interactive simulation and project page: http://burakoktenli.com/blade-maritime · Portfolio: https://burakoktenli.com/maritime The deposit includes all materials necessary to independently evaluate the hardware architecture and reproduce the mathematical analysis reported in this paper.

18. Dual-Use Ethics Statement

The BLADE-MARITIME governance pipeline is architecturally derived from the BLADE-EDGE defense variant (DOI: 10.5281/zenodo.19177472) and the BLADE-AV civilian variant (DOI: 10.5281/zenodo.19232130). This cross-domain portability demonstrates that authority-governed autonomy — continuous sensor trust fusion, graded authority with deliberation windows, and deterministic recovery — is a domain-agnostic safety principle applicable wherever autonomous systems exercise physical authority. The maritime effector is a normally-open safety relay governing authority; it is not a weapons release mechanism. The author affirms that no export-controlled (ITAR/EAR) technical data is disclosed beyond the self-assessment in Section 5, and that all engineering artifacts are published at a conceptual/architectural level consistent with open academic research under the fundamental research exclusion.

19. Version History

Version	Date	Key Changes
v1.0	Mar 26, 2026	Initial release. Maritime extensions described qualitatively.
v1.1	Mar 26, 2026	Added: export control notice, mathematical formalisms, performance tables, 15 external references, power budget, thermal management, conclusions, version history, acknowledgments.
v1.2	Mar 26, 2026	Fixed: α(H) jump discontinuity (γ=0.25 m^{-1} ensures continuity); MAIVA absolute-value staleness weight; Pfa notation; MIL-STD-810G edition consistency; D-S frame Θ defined; sonar equation added; LT6657 attribution corrected; STANAG 4586 body citation; Georgetown affiliation standardized; DEMON frequency band; sensor failure modes; duplicate export control header removed.
v1.3	Mar 27, 2026	Fixed: D-S formula first-term typo (m_hydro → m_MAD); Pfa U+2074 Unicode; MIL-STD-1399; date. Added: 7 visual diagrams (pipeline flow, system architecture, power chain, BOM breakdown, α(H) table, sensor coverage matrix, performance heatmap).
v1.4	Mar 27, 2026	Fixed: D-S /K normalization term restored; Power Monitor empty row removed from sensor matrix; BOM remaining-components line added ($1,832); Furuno GFE cost clarification; suggested citation version.
v2.3	Mar 27, 2026	Design overhaul: full BLADE-AV paper style adopted. Running header/footer, numbered sections, structured Zenodo metadata table, contents table, equation numbering, BLADE-AV-style comparison table, expanded regulatory alignment, dual-use ethics statement, related work lineage comparison.

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21. How to Cite

APA

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Note: External references are indexed in their respective publication databases with verifiable DOIs.

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