Tumi Robotics: System of Systems Architecture and Competition Strategy for the 2026 Maritime RobotX Challenge

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***Abstract*—Tumi Robotics, representing the Pontificia Universidad Católica del Perú (PUCP), is participating in the 2026 Maritime RobotX Challenge in Singapore, deploying an integrated System of Systems (SoS) framework. Designed to address the 2026 competition theme, "Storm Response: Technology in Action for Recovery and Relief", our multi-domain architecture integrates three specialized autonomous platforms: the Libertad Unmanned Surface Vehicle (USV), the Hatun Yaku Unmanned Underwater Vehicle (UUV), and the Urpi Unmanned Aerial Vehicle (UAV). Our systems engineering methodology establishes seamless inter-vehicle communication, decentralized task allocation, and modular hardware-software interoperability to execute high-complexity post-disaster maritime reconnaissance and intervention. Key technical contributions include an adaptive multi-agent coordination state machine, robust multi-modal perception combining 3D LiDAR, marine optical cameras, and Ultra-Short Baseline (USBL) hydroacoustic tracking, and real-time deep learning for obstacle detection and structural damage assessment. Through high-fidelity Gazebo Virtual RobotX (VRX) simulation and multi-phase empirical validation spanning PUCP mechatronic immersion tanks, the Parque de las Leyendas lagoon, and Pacific coastal trials in Pucusana and Paracas, Tumi Robotics demonstrates an agile, field-proven robotic ecosystem engineered for autonomous maritime recovery missions.**

***Index Terms*—System of Systems, Maritime RobotX Challenge, Unmanned Surface Vehicle, Unmanned Underwater Vehicle, Unmanned Aerial Vehicle, Autonomous Systems, Sensor Fusion, Decentralized Control.**

I. Introduction

A. Operational Context and Motivation

Coastal zones and maritime ports across the Pacific basin are increasingly exposed to acute climate disruptions, seismic tsunamis, and severe storm events. In Peru, recurrence of the El Niño Southern Oscillation (ENSO) and anomalous high-energy Pacific swells routinely inflict severe structural damage upon breakwaters, navigation buoys, seabed fuel pipelines, and port facilities. National statistics document economic contractions exceeding 1.1% of gross domestic product during major coastal events, compounded by the simultaneous shutdown of more than 94 commercial and artisanal maritime terminals.

Conventional post-storm damage inspection relies primarily upon human dive teams and crewed patrol craft operating in high-turbidity, strong-current environments. Such operations involve high operational latency, substantial financial expense, and severe life-safety risks. The deployment of heterogeneous autonomous unmanned systems operating collaboratively across air, surface, and subsea domains provides an effective paradigm for rapid, zero-risk assessment and recovery of impacted harbor infrastructure.

B. Alignment with RobotX 2026 Theme: Storm Response

The 2026 Maritime RobotX Challenge, organized by RoboNation and the Office of Naval Research (ONR) at The Promontory at Marina Bay in Singapore, focuses on the theme: *"Storm Response: Technology in Action for Recovery and Relief"* [1]. Competing teams are tasked with simulating an autonomous emergency response to a coastal port facility compromised by a catastrophic cyclone.

The 2026 challenge introduces a significant architectural evolution: the previous Wave Adaptive Modular Vessel (WAM-V) constraint has been sunsetted, replaced by an open mandate requiring multi-domain System of Systems (SoS) capability. Eligible teams must field an Uncrewed Surface Vessel (USV) acting in concert with an Uncrewed Underwater Vehicle (UUV) and/or an Uncrewed Aerial Vehicle (UAV). This paradigm requires continuous, coordinated autonomous missions spanning rapid aerial survey, navigational channel clearing, submerged cable and pipeline diagnostics, and acoustic search and recovery.

C. Institutional Framework and Systems Engineering Approach

Competing in representation of the Pontificia Universidad Católica del Perú (PUCP), the **Tumi Robotics** team builds upon more than a decade of institutional expertise in marine robotics, supported by ten funded national research grants and nine peer-reviewed IEEE publications in autonomous surface and subsea systems [2]–[6].

Our engineering methodology follows an adapted Systems Engineering (SE) V-model. Requirements derived directly from the RoboNation 2026 rules dictate platform mechanical sizing, communication topologies, and autonomy pipelines. The complete ecosystem integrates three specialized assets:

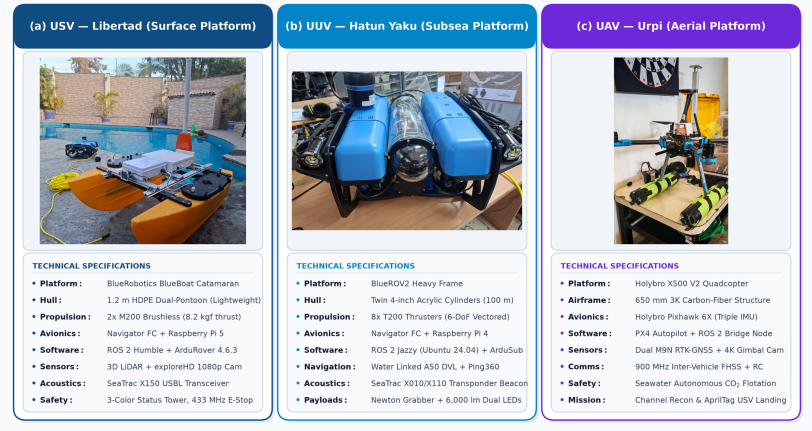


Fig. 1. Multi-platform robotic fleet deployed for the 2026 Maritime RobotX Challenge: (a) USV Libertad surface mothership, (b) Hatun Yaku subsea inspection UUV, and (c) Urpi UAV aerial scouting quadcopter.

1) **USV Libertad:** Autonomous catamaran surface vessel serving as communication gateway, acoustic tracking mothership, and surface reconnaissance node.
2) **Hatun Yaku UUV:** Vectored six-degree-of-freedom (6-DoF) underwater vehicle dedicated to subsea conduit inspection, pinger homing, and manipulation.
3) **Urpi UAV:** Carbon-fiber quadcopter optimized for long-range overhead mapping, rapid obstacle identification, and surface-to-air situational relay.

II. Competition Strategy and Mission Architecture

A. Task Selection and Prioritization Matrix

The 2026 RobotX Challenge Autonomy course requires teams to complete a spectrum of collaborative missions. To maximize scoring efficiency while managing operational risk, Tumi Robotics evaluated each task against three metrics: points return, system dependency, and probability of environmental failure. Table I outlines the resulting strategic prioritization.

TABLE I
Competition Task Prioritization and Platform Allocation

Mission Task	Primary Asset	Key Sensor Modality	Priority
Harbor Channel Navigation	USV Libertad	3D LiDAR + ExploreHD	Critical
Overhead Harbor Survey	Urpi UAV	4K Aerial Vision + GNSS	High
Acoustic Beacon Homing	USV + UUV	SeaTrac X150 USBL	Critical
Subsea Pipeline Inspection	Hatun Yaku UUV	Sonar + Dual 6k lm LED	High
Debris / Target Recovery	UUV Manipulator	Micro-Grabber + Vision	Medium
Cooperative Docking	USV + UAV	AprilTag Stereo Vision	Medium

B. Concept of Operations (CONOPS)

Our multi-domain Concept of Operations unfolds across three sequential phases designed to guarantee rapid harbor clearance, illustrated in Fig. 2:

- **Phase 1: Aerial Scouting and Channel Mapping:** Upon mission initiation, the Urpi UAV executes an autonomous vertical takeoff to an altitude of 20 m. Utilizing an onboard gimbaled camera and real-time color segmentation, the UAV rapidly charts safe navigable channels, detects floating navigational buoys (red/green channel markers), and identifies floating debris hazards. Georeferenced target coordinates are broadcast to the USV via an ad-hoc 900 MHz datalink.
- **Phase 2: Surface Transit and Dynamic Positioning:** Guided by the UAV's situational map, the USV Libertad navigates the channel using adaptive line-of-sight (ALOS) guidance and 3D LiDAR obstacle clustering. Upon reaching the designated underwater operations zone, Libertad engages dynamic positioning (DP), holding station within a sub-0.5 m circular error probable (CEP) despite tidal currents and wind drift.
- **Phase 3: Subsea Inspection and Acoustic Localization:** The USV activates its hull-mounted Blueprint Subsea SeaTrac X150 USBL transceiver to ping the ocean volume. The Hatun Yaku UUV descends autonomously, using acoustic positioning feedback and multibeam sonar to locate damaged submerged conduits. Upon detecting cracks or target markers, the UUV captures high-resolution video down to 50 mm geometric resolution, reporting completion before surface recovery.

C. Dynamic Mission Allocation and Health State Machine

Because multi-agent operations in maritime environments face battery depletion, acoustic multipath degradation, and radio dropouts, task allocation cannot remain static. We formulate task selection as a dynamic utility optimization problem. Let $\mathcal{A} = \{a_{\text{USV}}, a_{\text{UUV}}, a_{\text{UAV}}\}$ represent the fleet and

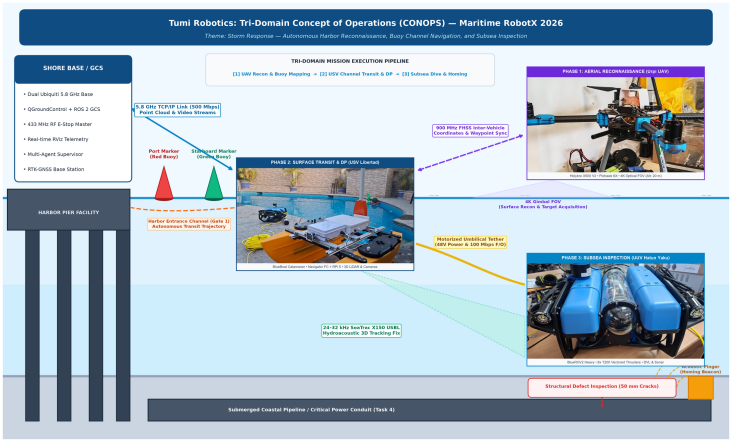


Fig. 2. System of Systems (SoS) tri-domain Concept of Operations (CONOPS) for the 2026 RobotX Storm Response challenge.

$\mathcal{T} = \{\tau_1, \tau_2, \ldots, \tau_M\}$ denote the active tasks. The allocation utility J is modeled as:

$$J(t) = \sum_{i \in \mathcal{A}} \sum_{j \in \mathcal{T}} x_{ij}(t) \cdot \left[\Omega_j \cdot H_i(t) \cdot e^{-\kappa \cdot d_{ij}}\right] - \sum_{i \in \mathcal{A}} C_{\text{risk}}(a_i, \tau_j) \tag{1}$$

where $x_{ij}(t) \in \{0, 1\}$ denotes task assignment, Ω_j is the competition task point value, d_{ij} is the Euclidean distance between agent i and task site j, and κ is a spatial penalty discount.

The fleet health metric $H_i(t) \in [0, 1]$ is computed in real time from three vital telemetry parameters:

$$H_i(t) = w_b \left(\frac{V_{\text{batt}}(t) - V_{\text{cutoff}}}{V_{\text{nom}} - V_{\text{cutoff}}} \right) + w_c \left(\frac{\text{RSSI}(t)}{\text{RSSI}_{\text{max}}} \right) + w_t (1 - \hat{T}_{\text{esc}}(t)) \tag{2}$$

where w_b, w_c, w_t are normalized weights corresponding to battery state of charge, RF communication link quality, and normalized electronic speed controller (ESC) thermal load, respectively. If an agent's health falls below a critical threshold ($H_i(t) < 0.25$), the mission manager triggers an automated abort state, shifting remaining tasks to alternative platforms or commanding safe return-to-launch (RTL).

III. Multi-Platform Mechanical and Electrical Systems

The integrated multi-domain robotic fleet engineered for the 2026 Maritime RobotX Challenge comprises the surface mothership, the subsea inspection vehicle, and the aerial scouting quadcopter, as introduced in Fig. 1.

A. USV Libertad (Surface Platform)

The USV Libertad is built upon the Blue Robotics BlueBoat catamaran hull architecture. The dual-pontoon high-density polyethylene (HDPE) hull provides superior transverse roll stability, high internal volumetric payload capacity, and low hydrodynamic drag under varied sea states [8].

Propulsion: The surface vehicle is propelled by twin Blue Robotics M200 brushless direct-current (BLDC) motors arranged in a differential thrust configuration. Capable of generating up to 8.2 kgf of static thrust per motor with weedless polycarbonate propellers, this setup provides responsive heading control without fragile mechanical rudders.

Avionics and Processing: The computing core comprises a Raspberry Pi 5 companion computer interfaced via high-speed UART to a Blue Robotics Navigator Flight Controller. The Navigator integrates a 6-axis IMU, magnetometer, and precision barometer, running ArduRover firmware. The Raspberry Pi 5 runs Ubuntu Linux and the ROS 2 Humble software suite, executing real-time trajectory tracking, LiDAR point-cloud processing, and network routing.

Power Distribution and Safety Electronics: The primary electrical bus operates at a nominal 24 VDC supplied by dual 14.8 V/22.2 V high-capacity marine lithium battery packs configured for balanced discharge. Custom power management includes high-efficiency step-down buck converters delivering regulated 12 VDC (sensors, USBL transceiver, Ubiquiti PoE) and 5 VDC (companion computer, logic relays). Heavy-duty 60A Solid State Relays (SSRs) provide instantaneous isolation of the motor power rail during safety interrupts.

Autonomy State Feedback Tower: To satisfy RobotX safety requirements, Libertad features an elevated, high-visibility 3-color light tower driven by a ULN2803 Darlington transistor array connected to GPIO outputs. The light states unambiguously announce the vehicle mode:

- **Red (Solid):** Manual remote control or emergency stop triggered.
- **Amber (Flashing):** Autonomous standby / mission paused.
- **Green (Solid):** Full autonomous mission execution active.

B. Hatun Yaku UUV (Subsea Platform)

The underwater subsystem employs Hatun Yaku, engineered upon a BlueROV2 Heavy frame, incorporating eight T200 thrusters in a vectored orientation. This geometry affords

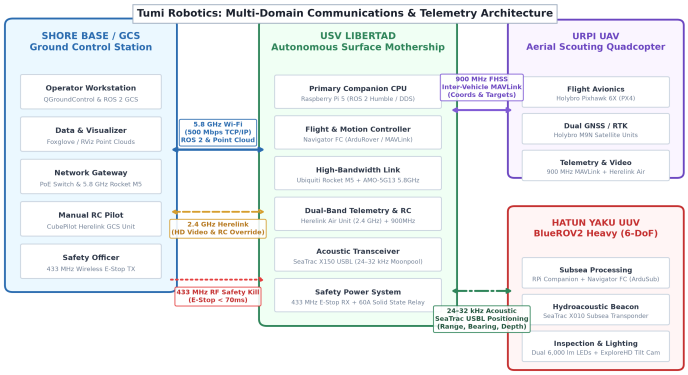


Fig. 3. Heterogeneous multi-frequency communications and telemetry architecture linking shore GCS, USV, UUV, and UAV.

complete six-degree-of-freedom control, permitting decoupled translation along the X (surge), Y (sway), and Z (heave) axes while simultaneously regulating roll, pitch, and yaw angles.

The main electronics enclosure consists of an acrylic cylinder rated to 100 m depth with anodized aluminum end caps. External subsea payloads include:

- **Optical Inspection:** An ExploreHD low-latency marine camera mounted on an active tilt mechanism, flanked by two high-output subsea LED arrays producing 6,000 lumens of diffuse illumination.
- **Acoustic Tracking Transponder:** A SeaTrac acoustic transponder synchronized with the USV's USBL transceiver for continuous underwater coordinate positioning.
- **Subsea Manipulator:** A single-function motorized grabber arm designed for retrieving debris markers or deploying recovery buoys.

C. Urpi UAV (Aerial Platform)

The Urpi UAV is a custom quadcopter engineered specifically for maritime littoral conditions. The airframe utilizes high-modulus 3K carbon-fiber arms and plates, combining rigid torsional strength with high gust resistance in coastal winds up to 22 knots.

Avionics: Flight control is managed by a Holybro Pixhawk 6X autopilot equipped with triple-redundant, temperature-stabilized IMUs and dual external M9N differential GNSS modules. The autopilot runs PX4/ArduPilot firmware, executing mission-plan waypoints with automated takeoff and landing capabilities.

Emergency Marine Flotation System: Operating aerial vehicles over open water introduces catastrophic loss risk during motor failure or ditching. Urpi features an autonomous water-contact sensing circuit connected to dual self-inflating CO_2 emergency flotation bladders. Upon detecting seawater contact, the actuator triggers within 50 ms, ensuring 100% positive buoyancy and preventing vehicle submersion.

D. Communications and Telemetry Network

Robust, uninterrupted telemetry between heterogeneous vehicles and the shore Ground Control Station (GCS) is vital. The network topology, illustrated in Fig. 3, employs a multi-tiered frequency strategy to prevent radio congestion:

- **High-Throughput Ground-to-USV Link (5.8 GHz):** An Ubiquiti Rocket M5 transceiver equipped with an AMO-5G13 13 dBi omnidirectional antenna provides a TCP/IP bridge operating at up to 500 Mbps over 2 km line-of-sight. This link carries live video feeds, point clouds, and telemetry to the shore GCS.
- **Manual Safety and RC Backup (2.4 GHz):** A CubePilot Herelink HD transmission system supplies redundant manual piloting control, mission pause capability, and emergency pilot override.
- **Inter-Vehicle and Telemetry Link (900 MHz):** Lightweight MAVLink telemetry and ROS 2 state broadcasts between the USV and UAV utilize 900 MHz FHSS transceivers, eliminating interference with 2.4/5.8 GHz payloads.
- **Subsea Hydroacoustic Link (24–32 kHz):** The Blueprint Subsea SeaTrac X150 USBL link communicates bidirectionally through the water column, exchanging depth, status words, and relative Cartesian fixes.

IV. Autonomy, Perception, and Software Framework

A. Distributed ROS 2 Ecosystem

Software across the fleet is built upon the Robot Operating System 2 (ROS 2 Humble) operating over Data Distribution Service (DDS) middleware [10]. The complete autonomy stack, structured into five hierarchical layers as illustrated in Fig. 4, coordinates real-time publish-subscribe communication, lifecycle nodes, and robust fault isolation. Micro-ROS and MAVROS agents bridge low-level autopilot microcontrollers (running ArduRover, ArduSub, and ArduCopter) to the high-level autonomy stack via direct DMA-backed serial links.

B. Perception Suite and Multi-Modal Sensor Fusion

Accurate state estimation and obstacle segmentation require fusing asynchronous data streams across diverse physical spectra:

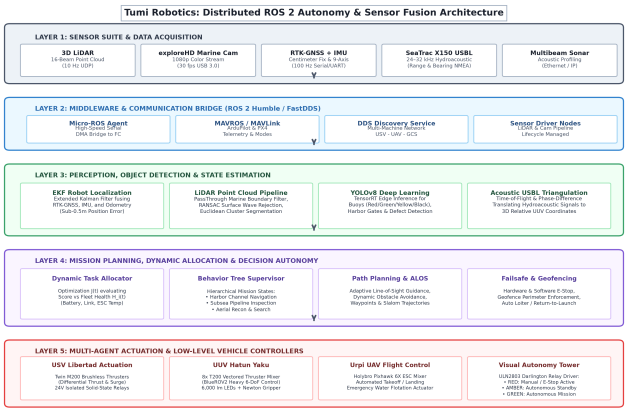


Fig. 4. Distributed ROS 2 software and autonomy architecture, showing data flow from hardware abstraction (Layer 1) through multi-modal perception and guidance to multi-agent task allocation (Layer 5).



Fig. 5. Multi-stage empirical field validation of the Tumi Robotics fleet: (a) Coastal Pacific swell trials in Bahía de Pucusana with autonomous USV and mast feedback, (b) In-water immersion and motorized tether deployment of Hatun Yaku UUV from USV Libertad in PUCP testing facilities, (c) High-altitude lake navigation trials at Laguna Langui (4,000 m ASL), and (d) Autonomous buoy channel obstacle slalom.

1) **Localization and Odometry:** An Extended Kalman Filter (EKF) integrates high-rate data from the Navigator 6-axis IMU, real-time kinematic (RTK) GNSS fixes, and thruster velocity odometry. The state vector $\mathbf{x} = [x, y, z, \phi, \theta, \psi, u, v, w, p, q, r]^T$ maintains estimated position errors below 0.35 m during continuous coastal transits.
2) **3D LiDAR Obstacle Segmentation:** A 16-beam 3D LiDAR mounted atop the USV mast generates 360-degree point clouds at 10 Hz. A PassThrough filter isolates the marine surface boundary, followed by RANSAC planar segmentation to reject ocean wave reflections. Surviving points are clustered using Euclidean distance segmentation, yielding oriented 3D bounding boxes with associated centroids and velocities.
3) **Camera Perception and Target Recognition:** An exploreHD optical camera captures 1080p color streams at 30 fps. Images pass to an onboard YOLOv8 neural network optimized via TensorRT for edge inference [9]. The network is trained on custom maritime datasets to detect competition elements: red/green/yellow/black navigation buoys, harbor dock gates, hazard flags, and floating life-rings.

C. Underwater Acoustic Localization and Homing

Subsea positioning is notoriously difficult due to extreme electromagnetic attenuation in seawater. Our system overcomes this through the Blueprint Subsea SeaTrac X150 USBL system mounted through an acoustically decoupled moonpool beneath the USV Libertad's port hull.

The transceiver emits an acoustic interrogation chirp within the 24–32 kHz band. The transponder onboard the Hatun Yaku UUV responds, allowing the USV array to measure acoustic time-of-flight (yielding slant range R) and phase difference across its multi-element hydrophone receiver (yielding azimuth angle θ and elevation angle ϕ). The relative Cartesian position is computed as:

$$\begin{bmatrix} x_u \\ y_u \\ z_u \end{bmatrix} = \begin{bmatrix} R\cos\phi\cos\theta \\ R\cos\phi\sin\theta \\ -R\sin\phi \end{bmatrix} \tag{3}$$

By transforming relative acoustic vectors into the world frame via the USV's RTK-GNSS and heading estimates, the mission manager tracks the UUV in world coordinates with an accuracy better than 1.2% of slant range.

D. Safety Systems and Emergency Stop (E-Stop) Protocol

Adhering strictly to RoboNation safety standards, Tumi Robotics implements a multi-layered, redundant Emergency Stop architecture: **Hardwired E-Stop:** An aft-deck IP67 latching switch directly disconnects primary 60A SSRs, cutting motor power within 20 ms. **Wireless RF E-Stop:** A dedicated 433 MHz receiver constantly monitors shore heartbeats, cutting motor power if signal drops > 500 ms while companion computers and avionics remain powered on an isolated circuit for logging. **Software Geofencing:** Autonomous software continuously checks vehicle position against boundary geofence polygons, immediately halting thrust, commanding loiter hold, and activating amber flashing indicators upon boundary excursion.

V. Experimental Validation and Field Testing

To de-risk the complex multi-domain system, Tumi Robotics formulated a four-stage test protocol progressing systematically from simulation to coastal maritime trials, as shown in Fig. 5.

A. Simulation in Gazebo VRX (Virtual RobotX)

Initial autonomy and navigation algorithms were validated in the open-source Gazebo Virtual RobotX (VRX) simulation environment [7]. VRX reproduces wave spectra, wind gusts, hydrodynamics, and buoyancy forces. Our control team evaluated path-following accuracy, obstacle slalom maneuvers, and automated docking routines under synthetic environmental disturbances prior to hardware implementation.

B. Laboratory Bench and Immersion Tank Testing

Physical subsystems were tested at the mechatronics laboratories and immersion tanks of the Pontificia Universidad Católica del Perú: **Thruster Bollard Pull:** Static bollard thrust tests verified differential drive curves of the M200 thrusters, ensuring symmetric torque across all throttle commands. **Hydrostatic Ballast Trimming:** The Hatun Yaku UUV was balanced in an immersion tank, achieving neutral buoyancy and zero static pitch/roll offset. **Hermetic Enclosure Testing:** Vacuum-decay leak tests confirmed IP68 integrity across all cable penetrators and end caps prior to water entry.

C. Inland Lagoon Field Trials: Parque de las Leyendas

Full system integration field trials were conducted at the Parque de las Leyendas freshwater lagoon in Lima, Peru, validating continuous 4-hour autonomous missions, autonomous optical identification and circumnavigation of buoy courses, and dynamic 3-color status tower state transitions under remote command.

D. Coastal Open-Sea Maritime Trials: Pucusana and Paracas

To achieve Technology Readiness Level 6 (TRL 6), the fleet was deployed in the Pacific Ocean at Bahía de Pucusana and Bahía de Paracas, facing representative ocean swells (0.6–1.4 m), 15-knot winds, and marine bio-turbidity. Field trials successfully validated high-speed 5.8 GHz telemetry beyond 1.5 km in saline air, USBL acoustic tracking in stratified seawater, and coordinated USV-UAV survey with real-time GPS coordinate handoff.

E. Quantitative Experimental Results

Table II summarizes the key quantitative performance metrics achieved across our experimental campaign.

TABLE II
System Performance Metrics from Field Validation

Performance Metric	Achieved Value	Specification
USV Waypoint Tracking CEP	0.34 ± 0.08 m	< 0.50 m
Dynamic Station Keeping Radius	0.42 m (in 12 kt wind)	< 1.00 m
Object Detection mAP@0.5	93.1%	$> 85.0\%$
USBL Acoustic Tracking Error	1.1% of slant range	$< 2.0\%$
Optical Defect Resolution	42 mm at 1.5 m depth	< 50 mm
RF E-Stop Trigger Latency	68 ms	< 100 ms
UAV Flight Endurance	22 min	> 18 min

VI. Conclusion and Singapore 2026 Roadmap

Tumi Robotics has engineered an agile, resilient, multi-domain System of Systems architecture tailored to the 2026 Maritime RobotX Challenge. By replacing single-hull dependencies with collaborative autonomy across the Libertad USV, Hatun Yaku UUV, and Urpi UAV, our design provides an effective operational solution for post-disaster harbor recovery and infrastructure restoration.

Our roadmap toward the November 2026 competition in Singapore includes three definitive milestones: **Q1–Q2 2026:** Gazebo VRX simulation refinement, ROS 2 inter-agent coordination tuning, and laboratory immersion basin validation; **Q3 2026:** Final open-sea integration trials in Paracas, customs clearance, and shipping of containerized equipment to Singapore on September 15, 2026; and **Q4 2026:** Arrival in Singapore, on-site calibration at The Promontory at Marina Bay, and competitive execution of the Maritime RobotX Challenge (November 8–14, 2026). Through rigorous systems engineering and field validation, the Tumi Robotics team from PUCP stands fully prepared to represent Peru on the global stage.

Acknowledgment

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TABLE III
APPENDIX A: COMPONENT LIST - USV LIBERTAD

Component	Vendor	Model/Type	Specs	Custom / Purchased	Cost	Year Of Purchase	Reasoning
Base Platform	Blue Robotics	BlueBoat	Catamaran hull, rugged modular design, payload capacity	Sponsored	N/A	2026	Provides a stable, reliable, and easily customizable physical base for the USV.
Propulsion	Blue Robotics	M200 Motors	Differential thrust configuration, 8.2 kgf max static thrust, weedless propellers	Purchased	N/A	2026	Main propulsion and steering. Reliable and marine-safe differential drive.
Companion CPU	Raspberry Pi Foundation	Raspberry Pi 5	8GB RAM, Broadcom BCM2712 quad-core Cortex-A76 at 2.4GHz	Purchased	N/A	2026	High-performance onboard processing for autonomy, ROS 2, and sensor fusion.
Flight Controller	Blue Robotics	Navigator Flight Controller	16 PWM channels, dual 6-axis IMUs, magnetometer, barometer	Purchased	N/A	2026	Seamless hardware integration with Raspberry Pi 5 running ArduRover.
Acoustic Tracking	Blueprint Subsea	SeaTrac X150 USBL	Multi-element hydrophone array, 24–32 kHz acoustic band, USB interface	Purchased	N/A	2026	Subsea acoustic localization and bidirectional tracking of the UUV.
Primary Comms	Ubiquiti	Rocket M5	5.8 GHz link, 500 Mbps, paired with AMO-5G13 omnidirectional antenna	Purchased	N/A	2026	Long-range, high-bandwidth TCP/IP link to Ground Control Station.
Backup Telemetry	CubePilot	Herelink	2.4 GHz HD Video Transmission and RC manual override	Purchased	N/A	2026	Provides fail-safe pilot override and low-latency situational video.
Power Architecture	Custom	24V Distributed Bus	5V, 12V, and 24V isolated buck converters, 60A Solid State Relays	Custom	N/A	2026	High-efficiency custom power distribution with emergency thruster isolation.
Visual Feedback	Custom	3-Color Tower	IP67 LED light tower driven by ULN2803 transistor driver and relays	Custom	N/A	2026	Mandatory visual status indicator announcing competition autonomy states.
Marine Camera	DeepWater Exploration	exploreHD	1080p low-latency marine USB camera, waterproof housing	Purchased	N/A	2026	High-definition visual perception for buoy and obstacle classification.

TABLE IV
APPENDIX B: COMPONENT LIST - UUV HATUN YAKU AND UAV URPI

Component	Vendor	Model/Type	Specs	Custom / Purchased	Cost	Year Of Purchase	Reasoning
UUV Hull Frame	Blue Robotics	Hatun Yaku	6-DoF heavy frame, acrylic pressure enclosure, 100m depth rating	Sponsored	N/A	2026	Modular subsea platform providing omnidirectional maneuverability.
UUV Propulsion	Blue Robotics	8x T200 Thrusters	Magnetic coupling, 5.25 kgf thrust each at 16V, vectored layout	Sponsored	N/A	2026	Independent control of surge, sway, heave, roll, pitch, and yaw.
UUV Lighting	Blue Robotics	Lumen Subsea LED	Dual subsea lights, 6,000 total lumens output, PWM brightness control	Purchased	N/A	2026	High-intensity illumination for deep-water pipeline and conduit inspection.
UUV Manipulator	Blue Robotics	Newton Gripper	Motorized subsea grabber, 100m depth rated, replaceable jaws	Purchased	N/A	2026	Enables physical interaction for debris recovery and marker deployment.
UUV Tracking	Blueprint Subsea	SeaTrac X010	Compact subsea acoustic transponder beacon	Purchased	N/A	2026	Operates with USV USBL transceiver for real-time subsea positioning.
UAV Airframe	Custom	Urpi Quadcopter	3K carbon-fiber rigid unibody, 650mm diagonal wheelbase	Custom	N/A	2026	Optimized torsional rigidity and marine wind resistance up to 22 knots.
UAV Avionics	Holybro	Pixhawk 6X	Triple redundant IMUs, Cortex-M7 at 480MHz, PX4/ArduPilot	Purchased	N/A	2026	High-reliability flight control with automated takeoff, waypoint, and RTL.
UAV GNSS	Holybro	M9N Dual GPS	Concurrent reception of GPS, GLONASS, Galileo, BeiDou	Purchased	N/A	2026	Redundant satellite positioning and compass orientation in open water.
UAV Flotation	Custom	Maritime Safety Bag	Seawater-contact sensor with dual CO2 auto-inflating emergency buoys	Custom	N/A	2026	Prevents sinking and ensures full platform recovery in case of water landing.
UAV Payload	RunCam	4K Aerial Cam	Ultra-HD 4K camera with 2-axis brushless stabilization gimbal	Purchased	N/A	2026	Wide-area overhead mapping and buoy channel identification for USV relay.

TABLE V
APPENDIX C: SYSTEM SAFETY AND FAILURE MODES AND EFFECTS ANALYSIS (FMEA)

Subsystem	Potential Failure Mode	Severity	Potential Causes	Detection Mechanism	Mitigation Strategy
Propulsion	Thruster entanglement with marine vegetation or debris	High	Floating ropes, kelp, or competition task rigging	ESC current telemetry spike and motor RPM drop	Reverse motor burst sequence; if stalled, isolate motor and revert to single-thruster limp-home mode.
Communications	Loss of 5.8 GHz primary Wi-Fi link to Shore GCS	Medium	RF multipath, excessive range, or antenna misalignment	Heartbeat timeout counter exceeds 1.5 seconds	Companion computer transitions state to Autonomous Hold; switches to 900 MHz backup telemetry or initiates RTL.
E-Stop System	Wireless RF safety kill command or transmitter loss	Critical	Shore safety officer intervention or transmitter battery death	Hardware RF receiver loss-of-signal output goes LOW	Dedicated SSRs disconnect motor power within 70 ms; companion computer logs event and activates flashing amber/red tower.
Navigation	RTK-GNSS satellite lock loss or multipath degradation	High	Ionospheric interference or physical harbor structure shadowing	GNSS fix status drops from RTK to Single; high covariance	EKF automatically transitions to dead-reckoning using LiDAR odometry and IMU integration; alerts GCS.
UUV Ingress	Water ingress into main electronics enclosure	Critical	O-ring seal failure, cracked acrylic end cap, or cable strain	Internal optoelectronic SOS leak sensor triggers	UUV aborts mission immediately; blows emergency ballast / full positive heave thrust to surface; USBL alert sent to USV.
UAV Ditching	In-flight propulsion failure or motor stall over water	Critical	Battery cell collapse or electronic speed controller burnout	Rapid descent rate detected by Pixhawk barometer/IMU	Emergency CO2 flotation bladders trigger via water-contact switch within 50 ms, keeping airframe buoyant for USV retrieval.