# Technical Design Report

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***Abstract*—This report presents the design and testing strategy of the Tongji University Marine Robotics Lab team for the 2026 Maritime RobotX Challenge. The system pairs T-Sky, an uncrewed aerial vehicle, with T-Wave, an uncrewed surface vehicle, targeting the Disruptive tiers of Tasks 1 and 3. The design coordinates aerial perception and resource handling with surface navigation, docking, and water delivery. Testing progresses from component verification and simulation to integrated field trials. Current results include perception validation, mission-planning simulations, visual-servo water-delivery integration, and RoboCommand run-start checks. Planned field trials will evaluate complete mission execution, recovery behaviour, and repeatability under representative operating conditions.**

***Index Terms*—marine robotics, uncrewed surface vehicles, uncrewed aerial vehicles, heterogeneous multi-robot systems, autonomous navigation**

## I. Overview

THE Tongji University Marine Robotics Lab (Tongji MRL) team is developing a cooperative aerial–surface robotic system for the 2026 Maritime RobotX Challenge. The system comprises an uncrewed aerial vehicle (UAV), named **T-Sky**, and an uncrewed surface vehicle (USV), named **T-Wave**. The two platforms are shown in Fig. 1.

The platforms are assigned complementary sensing and actuation roles. T-Sky supports aerial observation and resource pickup and delivery, while T-Wave provides surface navigation, docking, and directed water delivery. Their intended cooperation links aerial observations to surface route planning in Task 1, Safe Passage, and connects surface operations to aerial resource transport in Task 3, Coordinated Logistics. Each vehicle carries onboard sensing, computing, and control hardware. A mission manager on T-Wave is designed to coordinate task progression, while the Operator Control Station (OCS) provides supervision and communication with the official RoboCommand system.

The following sections explain the competition priorities and resource trade-offs, describe the system architecture and platform designs, and present the testing methodology, current results, and remaining integration work.

## II. Competition Strategy

Tongji MRL has selected a system comprising the T-Sky uncrewed aerial vehicle (UAV) and the T-Wave uncrewed surface vehicle (USV), targeting the Disruptive tier, the highest capability level, of Tasks 1 and 3 [1]. We have also defined preliminary mission logic for Task 4 in preparation for possible participation if the organisers permit a two-vehicle configuration. This strategy concentrates development on cooperation between aerial and surface platforms and balances our research interests with the personnel, preparation time, and funding available to the team.

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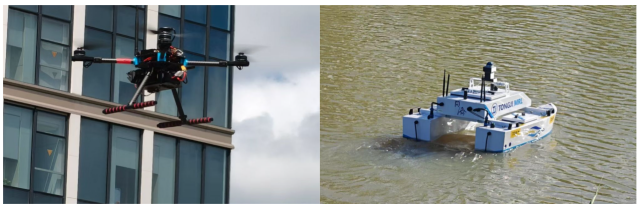


Fig. 1. Physical platforms of the Tongji MRL cooperative UAV–USV system.

### A. Task Interpretation and Research Motivation

Our task selection reflects the laboratory's research interests in heterogeneous multi-robot cooperation, aerial manipulation, and multi-agent planning. The selected tasks provide opportunities to investigate how complementary sensing and actuation capabilities can be coordinated to accomplish a shared mission.

We interpret Task 1, Safe Passage, as a cooperative navigation problem in which the information needed for surface motion is obtained from an aerial perspective. At the Disruptive tier, the safe passage may change during the USV's transit, and these changes are visible only to the UAV. The UAV must therefore maintain observation and communicate updates that allow the USV to revise its route [1]. Cooperative maritime inspection experiments by Santos et al. demonstrate the practical integration of UAV and USV capabilities [2]. For our system, Task 1 motivates a division of responsibility in which the UAV supplies observations of the changing passage and the USV converts those observations into feasible motion. Timely information exchange and consistent interpretation of the observations are central to this cooperation.

Task 3, Coordinated Logistics, connects surface operations with aerial manipulation through a sequence of dependent actions. At the Disruptive tier, the USV must identify the available docking bay, complete the firefighting operation, and communicate both the requested resource and its destination. The UAV must then autonomously retrieve the correct resource and deliver it to the designated location [1]. This task combines the flight and manipulation challenges reviewed by Ruggiero et al. with the dependencies between robot activities examined in multi-robot task allocation research [3], [4]. These connections motivate explicit conditions for transferring information and responsibility between the USV's docking and request interpretation and the UAV's pickup and delivery.

Task 4, Dynamic Incident Response, introduces changes to mission priorities and operating constraints during execution. We view it as an opportunity to study how coordinated behaviour can adapt while preserving progress toward the original mission. This interpretation is consistent with research on marine mission planning that considers vehicle capabilities, operational constraints, and changing mission conditions [5]. Our preliminary preparation specifies how to preserve task state, respond to a reported exclusion area, and determine when normal execution can safely resume.

### B. Team Resources and Competitive Priorities

Our competition team was established in 2026 and has limited personnel, with many members in their first or second year of undergraduate study. The preparation schedule must therefore accommodate training in robotics, system integration, and field operations alongside platform development. Simultaneously developing aerial, surface, and underwater systems would place substantial demands on the available supervision and engineering effort, reducing the time available to integrate and test each system.

The available budget also limits the feasibility of developing and supporting three vehicle classes. Adding an underwater platform would introduce further requirements for hardware, sensing, communications, maintenance, and testing. Focusing on the UAV and USV, with which the team is more familiar, allows funding and development effort to be concentrated on the capabilities required by Tasks 1 and 3. It also provides a manageable scope within which less experienced members can develop practical skills and contribute to complete mission functions.

Within this scope, the Disruptive tiers offer opportunities to pursue demanding cooperative behaviours and increase our scoring potential. Their value depends on successful execution, so development will progress from reliable individual behaviours to integrated task sequences. Mission scheduling must also account for the shared UAV: we plan to complete its surveillance responsibility in Task 1 before assigning it to resource delivery in Task 3. The final run plan will be informed by demonstrated completion reliability, expected task duration, and available energy. Our competitive strategy is thus to concentrate resources on completing the selected tasks at a high capability level, supported by sufficient integration and testing.

## III. Design Strategy

The system design translates the selected competition tasks into complementary responsibilities for T-Sky and T-Wave. T-Sky provides aerial observation and resource handling, while T-Wave performs surface navigation, docking, and water delivery. The resulting architecture combines onboard perception and control with a supervisory layer for coordinating task execution. Development focuses on the interfaces through which an observation from one vehicle enables an action by the other.

### A. System Architecture and Coordination

*1) Architecture:* Figure 2 presents the proposed architecture of the T-Wave USV and T-Sky UAV system, including onboard autonomy, communication interfaces, and the Operator Control Station (OCS). Each vehicle performs perception, planning, and control onboard, while the OCS provides vehicle monitoring and communication with the competition infrastructure.

Both vehicles use a Jetson Orin NX for perception and planning, coupled with a Pixhawk controller for vehicle control and payload actuation. On T-Wave, the Pixhawk 6C receives waypoint and spray commands from the autonomy stack. On T-Sky, the flight controller receives waypoint and grasp/release commands. ROS 2 interfaces connect the onboard software modules, carrying mission requests and execution feedback between the communication modules and the autonomy stacks. T-Wave additionally hosts the Mission Manager, which interfaces with its local autonomy stack and communication module.

AmovLab LQ Mesh provides the wireless network connecting the two vehicles and the OCS. Internal MQTT messaging uses this network to carry mission requests, observations, and task status. Within the OCS, QGroundControl provides vehicle-state monitoring through telemetry, while the RoboCommand Client handles official competition messages and reports. The client communicates with the competition infrastructure over external MQTT using the prescribed Protocol Buffers message definitions [6], [7]. The architecture thus assigns distinct interfaces to onboard software communication, team coordination, vehicle monitoring, and official reporting.

*2) Coordination:* The Mission Manager onboard T-Wave is designed to maintain the overall mission state and coordinate task progression across both vehicles. It issues requests to the local USV autonomy stack and communicates requests for UAV support through the internal MQTT network. Each vehicle executes the requested activity using its onboard perception, planning, and control functions, then returns progress and completion information. This feedback allows the Mission Manager to evaluate whether the conditions for the next activity have been satisfied.

For Task 1, coordination links aerial observation to surface navigation: T-Sky provides beacon observations that inform T-Wave's route planning and subsequent route updates. For Task 3, coordination links surface operations to aerial resource handling: T-Wave completes docking and water delivery, interprets the resource request, and communicates the required resource and destination to T-Sky for pickup and delivery. These exchanges require consistent position references, observation timestamps, and explicit execution status so that each vehicle can act on information relevant to the current mission state.

The OCS receives task updates for supervision and official reporting, while the onboard Mission Manager uses execution feedback to coordinate the vehicles. Integration work focuses on completing these information paths and verifying that task transitions occur only after the required observations and execution outcomes have been confirmed.

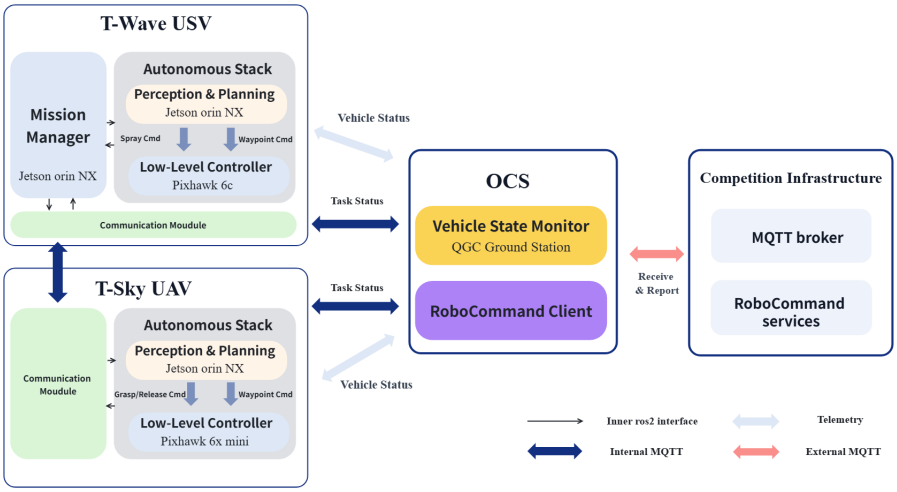



Fig. 2. System architecture and communication interfaces of the T-Wave USV and T-Sky UAV.

### B. USV Platform Design

*1) Competition Requirements:* T-Wave must navigate using UAV observations and route updates in Task 1, and perform docking, water delivery, and resource-request interpretation and relay in Task 3. These capabilities guide the propulsion, sensing, communication, and payload design.

The USV must fit within a $2.0 \times 1.0 \times 1.0$ m envelope, weigh no more than 60 kg, and use battery power with an open-circuit voltage not exceeding 60 V DC. Safety provisions include positive buoyancy, protected moving parts, manual control, status indication, and towing and lifting provisions. Onboard and independent wireless emergency stops must remove power from all propulsion systems and actuators and operate in a fail-safe manner [1].

*2) Hardware Design:*

*a) Platform Configuration:* T-Wave uses a customised USV-M1200 catamaran with two independently driven MOT-P75-290 thrusters. Differential propulsion provides forward motion and heading control for navigation and docking.

A Jetson Orin NX performs mission processing, while a Pixhawk 6C running ArduRover handles vehicle control. The MID-360 supplies geometric observations of obstacles and dock structures, the D435 supports navigation and dock recognition, and the gimbal-mounted OAK-D Lite supports payload aiming. Table I summarises the principal hardware.

*b) Power Management and Emergency Stop:* T-Wave uses separate batteries for port propulsion, starboard propulsion, and auxiliary equipment. Each propulsion battery supplies its thruster through a contactor and an electronic speed controller. The auxiliary power distribution is shown in Fig. 3. This circuit powers the onboard computer, sensors, communication equipment, flight controller, and mission payload. Regulated supplies provide the voltages required by these devices, including 12 V for the payload circuit and 5 V for the Pixhawk 6C. A 24 V, 2 A buck–boost module supplies the emergency-stop control circuit.

The propulsion cutoff and status-indication circuits are shown in Fig. 4. The propulsion contactors have normally open main contacts and require energised coils to maintain

TABLE I
T-WAVE HARDWARE CONFIGURATION.

| Subsystem | Configuration |
|---|---|
| Hull / propulsion | Customised USV-M1200 catamaran; two MOT-P75-290 thrusters and two FlyMonster 150 A marine ESCs |
| Compute / control | Jetson Orin NX; Pixhawk 6C running ArduRover |
| Positioning | UM982 receiver with two BT-560 antennas |
| Perception | MID-360, D435, and gimbal-mounted OAK-D Lite |
| Communication | AmovLab LQ Mesh for the internal network; G20/GR01 for manual control |
| Power | Three independent 24 V, 20 Ah battery packs |
| Water-delivery payload | YT260-U28H two-axis gimbal, UC-01 interface, camera, nozzle, and MOSFET-switched 12 V pump |
| Safety hardware | Propulsion contactors, onboard and remote stop interfaces, operating-state indicators, propeller guards, and towing and lifting provisions |

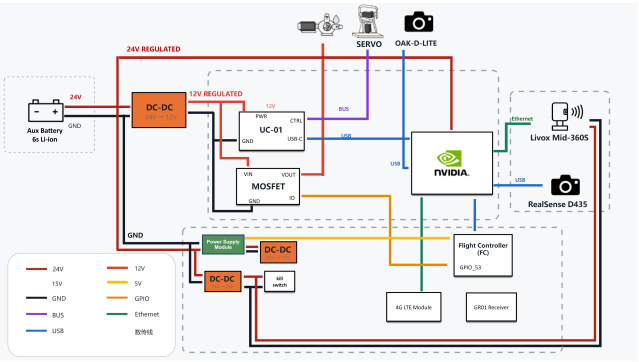



Fig. 3. Auxiliary power distribution and electrical connections of the onboard electronics and mission payload.

propulsion power. The onboard emergency-stop button directly interrupts the contactor-enable circuit. In the intended wireless-stop sequence, a received stop request or a configured failsafe event causes the Pixhawk 6C to set `GPIO_E` low, releasing the control relay and interrupting the same enable circuit. Both stop paths de-energise the contactor coils, opening the main contacts and disconnecting both propulsion supplies. Computing, communication, and status indication

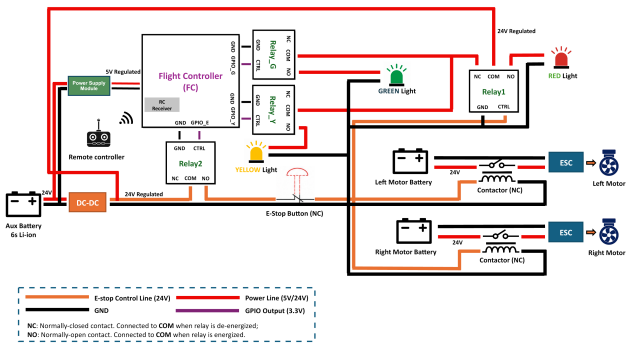



Fig. 4. Emergency-stop wiring for propulsion power cutoff and status indication.

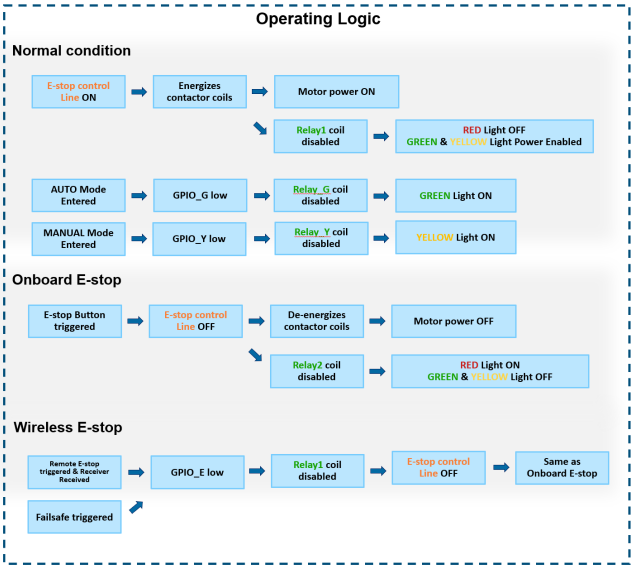



Fig. 5. Control logic for normal operation, onboard and wireless emergency stops, and status indication.

remain powered by the auxiliary circuit during a propulsion stop.

Fig. 5 summarises the operating logic for normal operation, onboard emergency stops, and wireless emergency stops. The status-indication logic assigns green to autonomous operation and yellow to manual operation. An emergency stop takes priority over both operating modes, switching on the red indicator and disabling the green and yellow indicators. System validation must confirm the shutdown and indication responses under each stop condition, including loss of the remote-control link. Verification must also cover hardware power cutoff for the pump and gimbal and safe behaviour when the emergency stop is reset.

*c) Water-Delivery Payload Design:* The water-delivery payload combines a two-axis gimbal, a camera, and a pump-driven nozzle. Figure 6 shows the gimbal and its mounting arrangement on T-Wave. The gimbal allows the nozzle to be aimed at the target window while the hull remains aligned within the docking bay. The Pixhawk 6C provides the pump-control signal, while a MOSFET switches the pump current from the auxiliary power circuit.

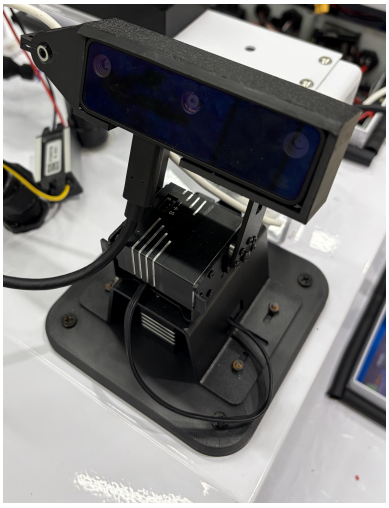


Fig. 6. Two-axis gimbal and mounting structure of the water-delivery payload on T-Wave.

### C. UAV Platform Design

*1) Competition Requirements:* T-Sky must detect and localise light beacons and provide updated observations for T-Wave's navigation in Task 1. In Task 3, it must respond to the USV's resource request by retrieving the specified resource tin and delivering it to the designated target area [1]. These roles guide the integration of aerial perception, inter-vehicle communication, and a grasping payload on a shared flight platform.

The maximum flight mass, including the battery, installed equipment, and carried resource, must not exceed 7 kg. The handbook specifies a flight ceiling of 60 m above mean sea level, subject to the final event restrictions. The UAV must use battery power, float in fresh water, and carry an independently powered emergency recovery light. A dedicated remote controller must support safety-pilot takeover, and the aircraft must be capable of both manual and autonomous takeoff and landing [1].

*2) Hardware Design:*

*a) Platform Configuration:* T-Sky is based on a modified Holybro X500 quadrotor equipped with retractable landing gear and a three-finger gripper. The quadrotor configuration supports hovering for aerial observation and controlled positioning during resource pickup and delivery. Integrating both roles on the same aircraft requires the sensing equipment and grasping mechanism to share the available mass and energy budgets. Table II summarises the principal hardware.

A Pixhawk 6X running PX4 handles flight stabilisation and state estimation, while a Jetson Orin NX executes perception and mission software. The intended autonomous command path uses PX4's offboard interface, which requires suitable state estimates and a continuous indication that the external controller remains active [8]. The camera is oriented forward and downward to support beacon observation and visual alignment with resources and delivery targets. AmovLab LQ Mesh provides the internal team network, and a SiK 433 MHz telemetry link supports flight monitoring through QGroundControl. A dedicated RC link provides the interface

TABLE II
T-SKY HARDWARE CONFIGURATION.

| Subsystem | Configuration |
|---|---|
| Airframe | Modified Holybro X500 quadrotor with retractable landing gear |
| Flight control | Pixhawk 6X running PX4 |
| Onboard computing | Jetson Orin NX |
| Navigation sensors | H-RTK ZED-F9P GNSS receiver and H-Flow module |
| Visual perception | Arducam B0495 global-shutter camera with a forward and downward view |
| Communication | AmovLab LQ Mesh for the internal network; dedicated RC link and SiK 433 MHz telemetry radio |
| Power | One 6S2P, 10,000 mAh battery pack; regulated 5 V supply for the gripper servo |
| Resource-handling payload | Three-finger gripper with servo actuation |



Fig. 7. Three-finger gripper installed on the T-Sky UAV.

for manual control.

*b) Power Management and Flight Safety:* T-Sky carries one 6S2P, 10,000 mAh battery per flight. Battery selection balances the energy needed for observation and transport against the mass available for onboard equipment and the carried resource. The flight energy budget must account for propulsion, computing, sensing, communication, and payload actuation, while preserving sufficient reserve for recovery. A regulated 5 V supply powers the gripper servo.

The dedicated RC path allows the safety pilot to take control of the aircraft. The flight-safety configuration addresses low battery, RC-link loss, and interruption of offboard commands through PX4's configurable failsafe functions [8]. The selected actions and trigger thresholds require verification on the final aircraft configuration, including confirmation that switching off the remote controller produces the safe response required by the competition.

*c) Resource-Handling Payload Design:* The resource-handling payload uses a three-finger gripper to capture, retain, and release a resource tin. Figure 7 shows the installed mechanism. The UAV positions the gripper relative to the selected resource, while servo actuation controls grasping and release. The mechanical layout must provide clearance between the gripper, landing gear, resource, and pickup surface throughout the approach and departure.

Visual alignment requires calibrated transformations between the camera, aircraft body, and gripper. These transformations account for the different mounting positions of the camera and grasping mechanism and relate visual target locations to the required grasping position. The resulting geometry must be included when converting visual observations into aircraft motion commands.

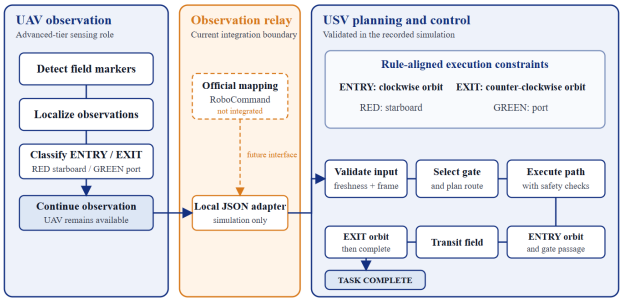



Fig. 8. Cooperative navigation workflow for Task 1, showing UAV observation, the observation relay interface, and USV planning and control.

Gripper placement and the carried resource affect the aircraft's mass distribution and flight response. Mechanical integration must therefore consider grasping geometry, resource retention, and flight control together, consistent with the coupled flight and manipulation problems discussed in the aerial manipulation literature [3]. Flight tests with representative resources are required to verify retention during transport and stable behaviour during pickup and release.

### D. Cooperative Navigation for Task 1

Figure 8 presents the observation-to-navigation workflow for Task 1, linking UAV observations to USV route planning and execution. The diagram separates aerial sensing, observation relay, and surface navigation. The current simulation uses a local JSON adapter to transfer observations to the planner; live observation transfer and task-specific RoboCommand reporting remain integration objectives.

The UAV perception pipeline separates beacon detection, temporal light-state classification, and position estimation. A single-class detector locates beacon enclosures, while tracking and region-of-interest checks maintain observations between detector updates. Brightness, colour, and temporal history are then used to distinguish unlit, flashing, and steady-light states. This separation allows the detector to identify the physical enclosure while the temporal classifier interprets its changing signal.

Beacon positions are provisionally estimated by intersecting a camera ray with an assumed beacon-height plane. This calculation depends on camera calibration, aircraft pose, timestamp alignment, and a consistent height reference. Detection validity, light-state validity, and position validity are therefore represented separately. A target may remain visually detected while its position or light state is unsuitable for planning. Observation transfer must preserve these validity indicators together with the coordinate frame and observation time.

The surface planner represents each confirmed red/green buoy pair in a local frame defined by the pair's position and orientation. This supports passages with different headings and allows crossing and clearance checks to be expressed

relative to each opening. The route must preserve the required passing sides and the entry and exit manoeuvres. Local obstacle response is evaluated separately from route feasibility, so steering and speed adjustments must remain compatible with the task constraints. Constructing valid buoy pairs and determining their traversal order are therefore essential steps between perception and route execution.

The Disruptive-tier objective extends this baseline to changes observed during the USV's transit. The intended extension maintains UAV observation, confirms changes in beacon state, and updates the route from the USV's current position. An accepted change must trigger a new feasibility check for any affected route segment. If observations become stale or no valid continuation is available, the planned response is to suspend task progression and enter a controlled holding state. Live observation transfer and dynamic route updates remain integration objectives beyond the recorded baseline simulations.

### *E. Coordinated Logistics for Task 3*

Task 3 is organised around dependencies between docking, water delivery, request interpretation, and aerial transport. The onboard Mission Manager is designed to advance through these activities when the required preceding outcomes have been confirmed. Making these dependencies explicit supports coordination between robots whose actions contribute to a shared task [4].

The planned USV approach and docking pipeline is shown in Fig. 9. The sequence begins with a coarse UAV observation identifying a dock region, followed by local USV search and bay inspection. MID-360 geometry and camera observations are assigned to resolving the docking structure and identifying the available bay. The interface distinguishes the coarse search region from the precise entrance pose needed for terminal control. Once an entrance pose has been selected and expressed in the navigation frame, `DockPlanner` organises the manoeuvre into approach, alignment, entry, and stopping stages. This decomposition makes heading correction and clearance assessment explicit before the vessel enters the confined bay.

After docking is confirmed and reported, the water-delivery sequence identifies the active target window and guides nozzle alignment. The perception interface distinguishes current, temporarily retained, and stale depth information. The intended pump-activation logic requires valid target observations, usable depth information, acceptable nozzle alignment, and the necessary gimbal and safety conditions. Completion is determined from the specified visual success indication.

The subsequent temporal decoder preserves the order of the two-colour resource request: the first colour identifies the required resource and the second identifies its destination. The decoded request is sent to the UAV through the internal communication network and reported to the competition infrastructure through the OCS. This connects the outcome of the USV's water-delivery operation to the UAV's resource-handling mission.

The intended UAV sequence locates the resource platform, identifies the requested tin, aligns the gripper, retrieves the resource, and transports it to the designated delivery area. Relative visual alignment is planned for the final approach, using camera observations to refine aircraft motion near the target. This follows the visual-servoing principle of incorporating visual measurements into the control loop [9]. Camera-to-gripper calibration, suitable approach-height information, and observable criteria for successful pickup and release are prerequisites for this sequence.

The docking planner has been exercised in simulation, while the continuous chain connecting live bay identification, physical docking, water-delivery confirmation, request decoding, and autonomous pickup and delivery remains under integration. The detailed evidence and remaining verification steps are presented in the Testing Strategy.

## IV. Testing Strategy

Our testing strategy follows the dependencies of the UAV–USV system and the requirements of the selected competition tasks. It progresses from component verification to coordinated mission validation, with particular attention to safety, perception under changing conditions, and reliable transfer of information between the two vehicles.

### *A. Testing Methodology*

The methodology distinguishes verification of individual requirements from validation of the integrated system in its intended operating environment [10]. Competition requirements determine the behaviours to be tested, while the system architecture determines the integration order. Safety functions and interfaces shared by multiple mission stages receive priority because failures in these elements can invalidate subsequent trials.

Testing proceeds through four levels. Bench tests check power distribution, sensors, actuators, emergency stops, and manual control. Offline evaluation, recorded-data replay, and simulation then examine perception errors, coordinate transformations, planning geometry, and mission-state transitions. Subsystem trials connect the installed sensors, onboard computers, controllers, and payloads on each vehicle. Finally, coordinated field trials exercise the complete mission sequence, including inter-vehicle communication and RoboCommand reporting.

For each planned trial, the test record will identify the requirement, hardware and software configuration, initial conditions, acceptance criterion, and supporting evidence. Measurements will include task completion time, positioning error, communication continuity, and operator interventions, as appropriate. Numerical tolerances will be established from the measured task geometry and required operating clearances. Photographs and video will document the setup and observed behaviour, supported by timestamped sensor, control, and communication logs. Failed trials will be retained and repeated after corrective changes.

### *B. Test Plan and Schedule*

The remaining integration campaign is scheduled for 1–15 October 2026. Table III divides this period into component

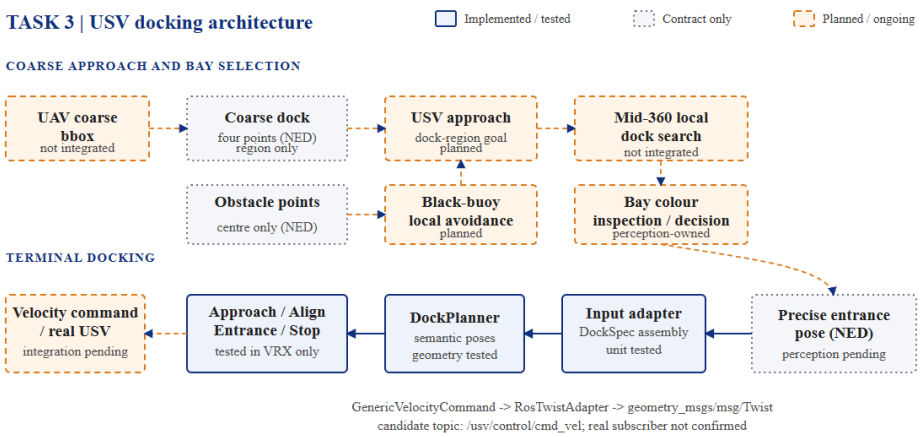



Fig. 9. USV approach and docking architecture for Task 3. The diagram distinguishes tested components, defined interfaces, and planned integration.



Fig. 10. Preliminary USV pump and water-jet demonstration. The photograph documents water delivery during the component test.

verification, individual-vehicle trials, and coordinated mission testing. These are planned working windows; progression to a more demanding trial depends on completion of the preceding safety and functional checks.

### C. Completed Tests and Current Results

Table V in Appendix A summarises the available test evidence across both platforms and identifies the validation still required for complete mission execution.

*1) Platform and Payload Tests:* Initial USV payload tests verified the Pixhawk-to-MOSFET pump-control interface and demonstrated a water jet of approximately 3 m. Figure 10 documents the preliminary spray test. Subsequent integration has brought the Task 3 visual-servo water-delivery chain into operation, connecting visual targeting, gimbal control, and pump actuation. This establishes functional integration of the payload; its repeatability under field conditions remains part of the October campaign.

UAV development tests have demonstrated gripper opening, closing, resource retention and release, together with indoor and outdoor flight and manual/autonomous control. The next stage evaluates these functions together during repeated pickup, loaded-flight, and delivery trials.

*2) Perception Tests:* For Task 1, evaluation using the earlier beacon design yielded mean average precision (mAP) scores of 0.9700 at an intersection-over-union threshold of 0.50 (mAP@0.50) and 0.7228 averaged over thresholds from 0.50 to 0.95 (mAP@0.50:0.95). Four video replays produced 1,586 frame records over 61.67 s. The examples in Fig. 11 show both retained flashing states and failure cases, including false steady-blue classifications and unresolved unlit targets. These observations identify temporal state estimation and viewpoint sensitivity as priorities for further testing. Data collection for the revised beacon design is now complete; model updating and evaluation on the new data are scheduled for October.

Table IV summarises the earlier offline validation results for the Task 3 perception components, while Fig. 12 shows representative detection examples. Training histories for Dock Structure V2, Docking Light V2, and Sprayer Window V2 are provided in Fig. 15 in Appendix A. Repeated vehicle trials will evaluate perception performance using the installed cameras and onboard computers under field conditions.

*3) Planning and Simulation Tests:* The Task 1 planner passed all 44 final offline tests covering gate geometry, progress tracking, obstacle-related logic, and clearance checks. In a simulation with large heading changes, the USV crossed seven gates in sequence, completed both required orbits, and reached `TASK_COMPLETE` in 806.7 s. Figure 13 shows the recorded trajectory relative to the simulated gate arrangement.

For Task 3 docking, 37 local software tests checked geometry, transformations, command fields, and clearance. In Gazebo/VRX [11], a 30 N simulated approach timed out; a subsequent 45 N run reached `DONE` at 284 s within the local 300 s test window. Final position and heading errors were 0.379 m and 0.115°, respectively. These simulations support further controller integration and parameter tuning; physical trials will evaluate the behaviour of T-Wave under actual disturbances.

*4) Communication Tests:* An earlier two-computer test exercised the official `rc-test` server [7], including a run declaration, independent 2 Hz reports for T-Wave and T-Sky, and receipt of a matching `RunStart` message. Figure 14 summarises the intended start sequence: the OCS receives the course configuration, declares the participating vehicles, and

TABLE III
PLANNED INTEGRATION AND TESTING CAMPAIGN, OCTOBER 2026.

| Window | Test activities | Completion criteria |
|---|---|---|
| 1–4 Oct. | Verify the installed safety and control interfaces; calibrate sensors and coordinate frames; update and evaluate the Task 1 detector using the newly collected beacon data; complete remaining Task 3 perception and interface checks. | Documented safety responses, consistent sensor and vehicle coordinates, reproducible perception results, and valid commands reaching the intended controller. |
| 5–9 Oct. | Conduct individual-vehicle trials: USV navigation, obstacle avoidance, bay approach, docking, and visual-servo water delivery; UAV observation, resource pickup, loaded flight, and release. | Each subsystem completes its defined sequence with recorded errors, interventions, and failure cases using the installed hardware. |
| 10–15 Oct. | Integrate live vehicle states with the OCS; test the Task 1 observation-to-navigation handoff and the Task 3 docking-to-delivery sequence; repeat trials under varied conditions and exercise communication recovery. | Complete mission records linking perception, planning, vehicle actions, and required reports, with outcomes and operator interventions recorded for every attempt. |
| Before competition | Repeat configuration checks after transport and assembly; verify local lighting, communications, manual recovery, and the competition run-start procedure. | A checked operating configuration and a recorded rehearsal using the final vehicles, payloads, and OCS. |

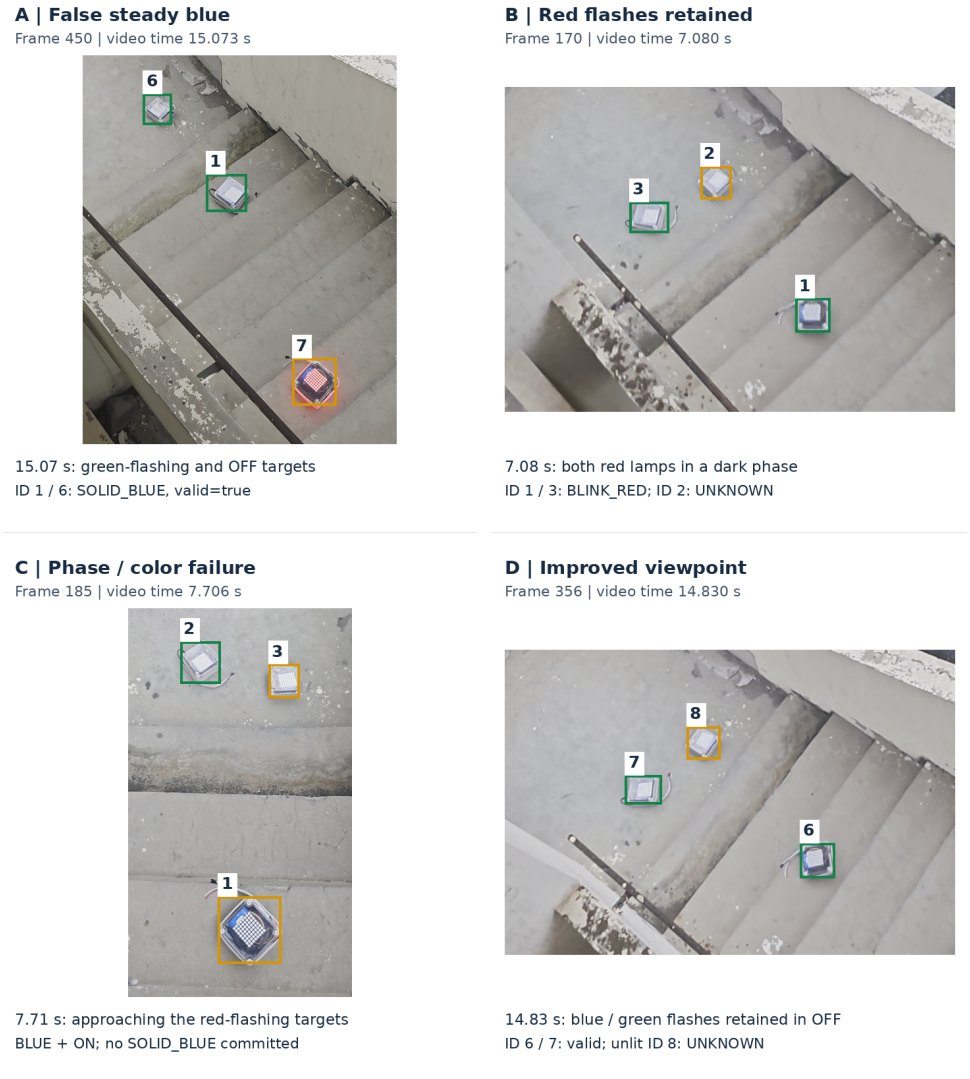


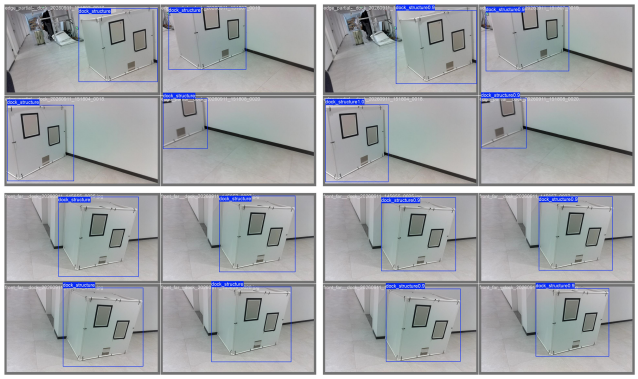

Fig. 11. Task 1 video-replay examples using the earlier beacon design. The frames illustrate false steady-blue classifications, retention of flashing states during dark phases, viewpoint-dependent errors, and unresolved unlit targets.

forwards their heartbeats. Mission dispatch requires vehicle readiness and a `RunStart` message matching the team and declaration sequence.

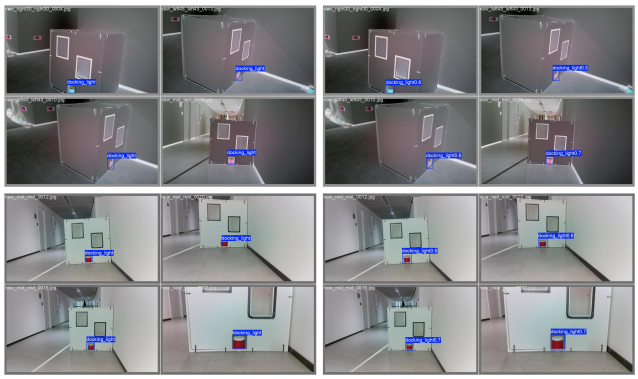
Internal MQTT heartbeat exchange and reconnection were also checked. Integration with live vehicle-state sources and validation of mission-start dispatch and continuous mission

TABLE IV
TASK 3 PERCEPTION VALIDATION RESULTS. METRIC PAIRS DENOTE MAP@0.50 / MAP@0.50:0.95.

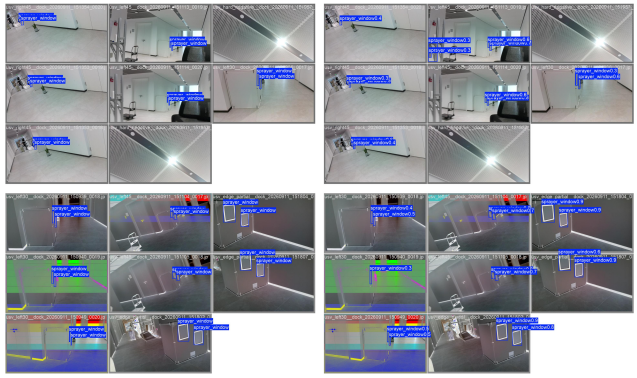
| Component | Validation result | Evaluation scope and limitations |
|---|---|---|
| Dock Structure V2 | 0.995 / ∼0.761 | Offline validation and OAK development tests; evaluation on the final onboard configuration remains pending. |
| Docking Light V2 | 0.946 / 0.581 | Offline detector validation and colour-based bay-selection logic; physical bay selection remains to be evaluated. |
| Sprayer Window V2 | 0.922 / 0.611 | Offline validation and close-range OAK RGB/depth checks; robustness during repeated field trials remains to be quantified. |
| Dock Face Pose V3 | Box: 0.986 / 0.753; pose: 0.954 / 0.902 | Training completed; `REAR` class handling, entrance-pose conversion, and north–east–down frame validation remain open. |



(a) Dock Structure V2



(b) Docking Light V2



(c) Sprayer Window V2

Fig. 12. Offline validation examples for the Task 3 perception components: dock structures, docking lights, and spray windows.

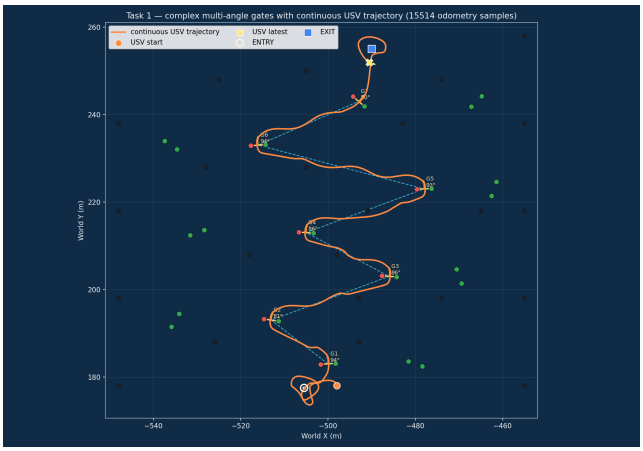



Fig. 13. Recorded Task 1 trajectory in a simulation with large heading changes. The plotted course contains seven gates between the entry and exit markers. The run completed the gate sequence and both required orbits in 806.7 s.

traffic remain scheduled for October.

### *D. Remaining Tests Before Competition*

The next tests connect the demonstrated components into complete task sequences. For Task 1, the priorities are evaluation on the revised beacons, synchronised camera and vehicle-pose data, reliable UAV-to-USV observation transfer, and physical navigation through changing gate configurations. Performance will be assessed using beacon-state accuracy, localisation error, legal gate crossings, and response to updated observations.

For Task 3, testing will combine bay identification, docking, visual-servo aiming, water delivery, and UAV resource transport. Water-delivery completion will be evaluated using the required target-indicator transition. Resource trials will verify the requested colour, secure pickup, retention during flight, and release within the intended delivery region. Repeated trials will vary approach direction, target distance, lighting, and initial vehicle position.

Safety verification will measure the USV emergency-stop response, including transmitter-power loss, removal of power from propulsion and actuators, and the latched stop state. The wireless-stop acceptance criterion is a response of less than 2 s [1]. UAV trials will verify manual takeover, configured recovery behaviour, payload retention, and endurance at the intended operating mass.

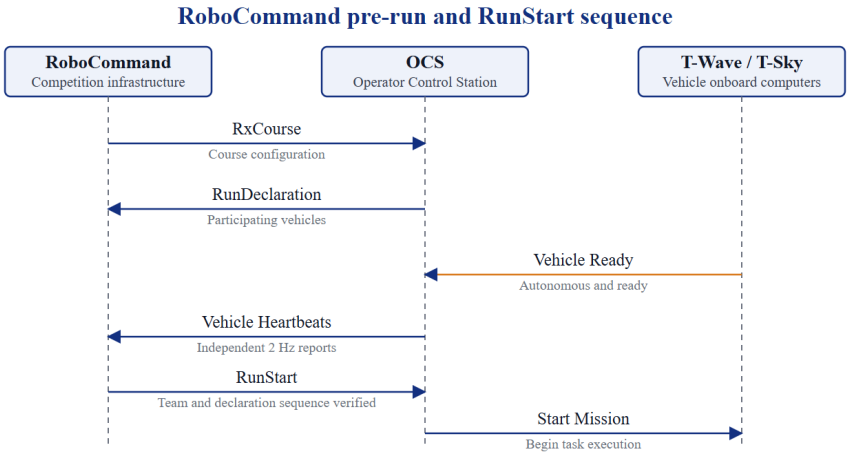



Fig. 14. Planned RoboCommand pre-run and mission-start sequence. The OCS coordinates course configuration, vehicle declaration, heartbeats, readiness checks, and mission dispatch.

The final rehearsals will include the OCS run-start sequence, live inter-vehicle communication, task execution, and the required reports. All attempts will contribute to the reported completion rate, with trial counts, completion times, and interventions stated explicitly. Task 4 response tests will be added if participation with the selected two-vehicle configuration is confirmed.

## ACKNOWLEDGEMENTS

Tongji MRL thanks Kun Cao for technical guidance and system-integration supervision. The team also thanks Tongji University and the Shanghai Research Institute for Intelligent Autonomous Systems (SRIAS), Tongji University, for laboratory resources and test-site support for platform development and field testing. No external sponsor support is claimed.

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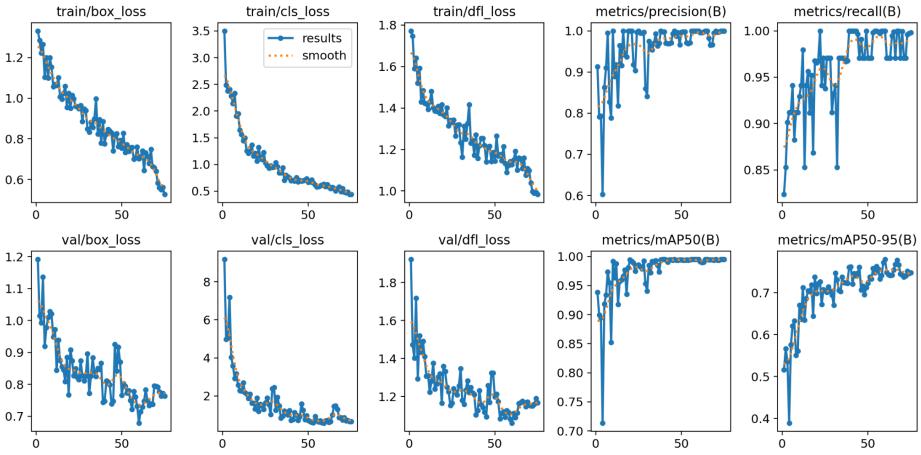
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# APPENDIX A
# EVIDENCE AND CONFIGURATION INDEX

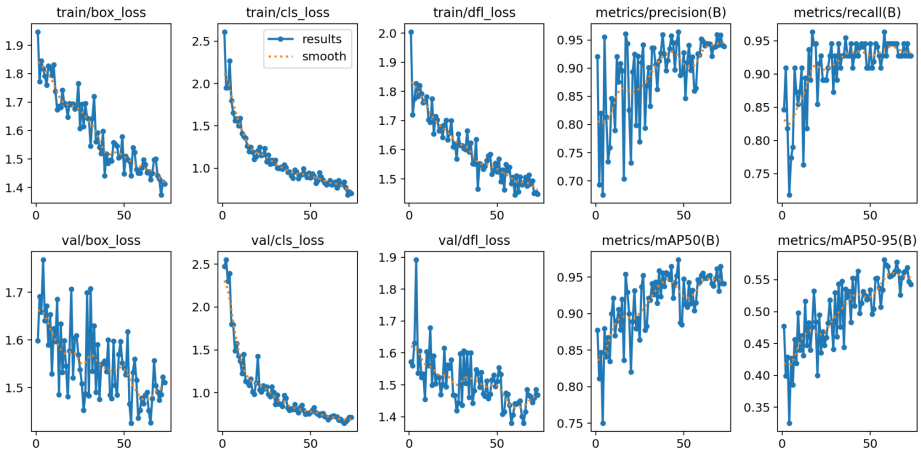
Table V summarises the available test evidence and remaining validation across the two platforms. Training histories for the Task 3 detection components are provided in Fig. 15.

TABLE V
EVIDENCE INCLUDED IN THE REPORT.

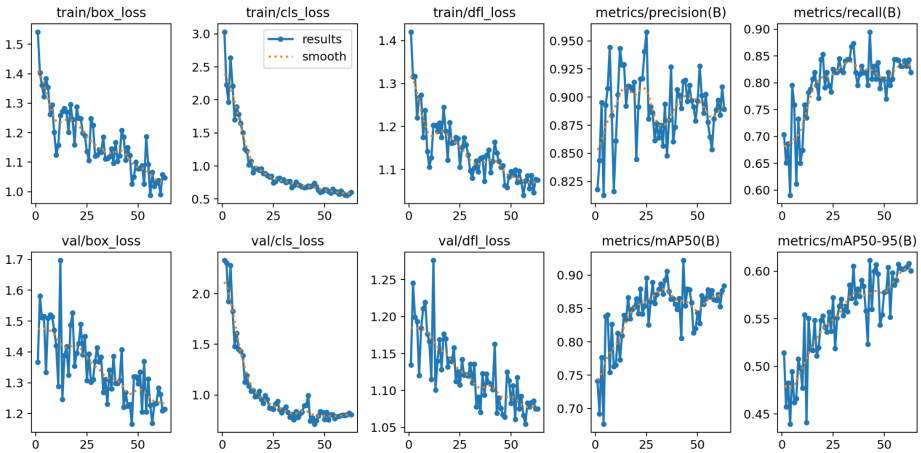
| **Evidence group** | **Recorded result** | **Scope and remaining validation** |
|---|---|---|
| T-Wave hardware | Three 24 V/20 Ah power domains; Pixhawk 6C, Orin NX, UM982, MID-360, D435, OAK-D Lite, RC and payload documented | Final mass, centre of gravity, endurance, sensor extrinsics, wiring revisions, RTK fix, emergency-stop timing, and flotation/lifting/recovery checks remain open |
| Water payload | Pump control, aiming and RC takeover checked; preliminary jet range about 3 m. Task 3 visual targeting, gimbal control and pump actuation integrated | Repeated field trials, aiming error, delivery success, target-indicator transitions and endurance remain to be quantified |
| Task 3 docking | All 37 local software tests passed; one 45 N VRX run reached `DONE` at 284 s with 0.379 m final position error and 0.115° heading error | Simulation with a known bay; physical docking, live bay selection and integrated task execution remain to be validated |
| T-Sky hardware | Pixhawk 6X/PX4, Orin NX, ZED-F9P, B0495, H-Flow, SiK 433 MHz and gripper documented; indoor/outdoor flight, flotation and safety checks reported | Final mass, centre of gravity, endurance, RTK, loaded flight and recovery require repeated trials; link results to PX4 configurations and annotated logs |
| Task 1 perception | Earlier-beacon detector precision 0.9688, recall 0.8884, mAP@0.50 0.9700; four replays and two ground checks. Revised-beacon data collection completed | Model updating and evaluation on revised beacons, live calibrated pose and UAV-to-USV handoff remain open |
| Task 1 planning | 180 earlier offline tests; all 44 final tests passed; baseline simulations and simulations with large heading changes completed | Deterministic simulation with a provisional observation interface; execution through MAVROS on the USV remains untested |
| Task 3 USV perception | Dock Structure, Docking Light, Sprayer Window and Dock Face Pose metrics; OAK RGB/depth and gimbal coordinate-transform checks | Final onboard perception, calibrated entrance pose, physical docking and complete Task 3 field trials remain pending |
| Communications | Official `rc-test` declaration, independent 2 Hz reports and `RunStart`; internal MQTT heartbeat/recovery checks | Competition network, live vehicle adapters and complete mission-message integration remain to be validated |
| Task 4 | Response concept only | Eligibility and participation unconfirmed; no test result claimed |




(a) Dock Structure V2




(b) Docking Light V2




(c) Sprayer Window V2

Fig. 15. USV perception training histories supplied in the 23 September evidence package.