



U.Stall

Hochschule Esslingen

Esslingen am Neckar, Baden-Württemberg, Germany

2026 MATE ROV Competition

Technical Documentation — Explorer Class

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Jan Vorsprach	Electrical / Hardware Lead
Johann Spielvogel	Software Lead
Katharina Darscht	Mechanical / Manufacturing
Iheb Elleuch	Electrical / Sensors
Jakob Hagmann	Pilot / Operations Lead
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Mentors: Prof. Dr. Oliver Dürr | Thomas Hoover | Julia Würtz

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Abstract

U.Stall is the ROV competition team of Hochschule Esslingen, Germany. For the 2026 MATE ROV Explorer Class competition, the team designed, built, and tested a fully modular underwater vehicle built around a two-box aluminium chassis and a standardised Common Interface coupling system. The vehicle carries six BlueRobotics T200 thrusters in a triangular arrangement providing four directly controllable degrees of freedom, active roll and pitch stabilisation via IMU-driven differential thrust, and slight positive buoyancy for passive surface recovery on any failure. Key 2026 innovations include: a four-DOF underwater gripper arm with self-locking worm-gear joints developed by a dedicated student project group; a sealed FDM buoyancy module replacing the 2025 polystyrene block; and a Power-over-Ethernet Raspberry Pi camera architecture replacing the 2025 USB design. The communication backbone was migrated from UART to CAN bus for noise-immunity over the 25 m tether. The surface control system runs a C#/WPF GUI connected to a MicroPython embedded stack via CAN bus, implementing a robust handshake and state-machine safety protocol. In addition to the ROV, the team built and operated an autonomous profiling float using a syringe-based buoyancy engine and ESP32 data-logging system. The document follows the 2026 MATE ROV Technical Documentation requirements for the Explorer Class.



Figure 1 The U.Stall Team

1. Company Profile and Team

1.1 Company Overview

U.Stall is the student ROV team of Hochschule Esslingen, located in Esslingen am Neckar, Baden-Württemberg, Germany. The team was established to participate in the MATE ROV Competition and to provide students with hands-on engineering experience across mechanical design, electronics, embedded software, and project management disciplines. The name "U.Stall" refers to the underwater nature of the vehicle ("U" for underwater) and the team's spirit of perseverance in engineering challenges.

Founded in 2023, the U.Stall is located at the Göppingen Campus of Esslingen University. The University provides workshop access. As a team, we believe that sharing our knowledge helps not only others but also us in getting better.

1.2 Team Members and Roles

Name	Role / Responsibilities
Jakob Kerber	Team Captain / Mechanical Lead
Jan Vorsprach	Electrical / Hardware Lead
Johann Spielvogel	Software Lead
Katharina Darscht	Mechanical / Manufacturing
Iheb Elleuch	Electrical / Sensors
Jakob Hagmann	Pilot / Operations Lead
Levi Reichert	Safety Officer
Lena Maier	Mechanical / Manufacturing
Francesco Torres Vila	Software
Berke Hakki Ari	Float
Bijan Ko	Accounting / Project Management
Luka Sokol	Accounting / Project Management
Laurin Layh	Accounting / Project Management

1.3 Mentor(s)

Professor Dr. Oliver Dürr and Thomas Hoover serve as faculty advisors. Advising as alumnus and founder of the U.Stall, Julia Würtz mentors the U.Stall.

1.4 Project Management and Schedule

The team operates on a semester-based schedule aligned with the Hochschule Esslingen academic calendar. Development began in autumn 2025 and culminated in the Regional competition in April 2026 and the World Championship qualifier video shoot in May 2026. Sub-teams for mechanical, electrical, software, and the gripper-arm student project worked in parallel, interfacing at regular integration meetings.

Milestone	Target / Actual Date	Status
Project Kickoff	01.09.2025	Complete
First Pool Integration Test	23.04.2026	Complete
Regional Product Demonstration	25.04.2026	Complete
Qualifier Video — main shoot	13.05.2026	Complete
Technical Documentation Submission	21.05.2026	PENDING
MATE World Championship	21.06.-30.06.2026	UPCOMING

As is common with student projects, a very dynamic and flexible project management was implemented. The only “hard” deadlines are the submission dates with both mentors and the administration team regularly checking progress and reminding the team.

Having launched in April this year, an official task tracking tool has been implemented allowing for easy tracking of progress and capacities of team members. Results of this change have yet to be evaluated.

2. Mechanical Subsystem

The mechanical subsystem was developed against three primary design goals: mission effectiveness, deployment reliability, and in-field serviceability. The two-box chassis architecture was chosen to allow electrical, software, and mechanical development to proceed in parallel, with the Common Interface as the standardised boundary between disciplines. The Navigation Box (top) carries all propulsion electronics and the six thrusters; the Exploration Box (bottom) carries task-specific electronics and all modular tool interfaces. The 2026 mechanical innovations are: a four-DOF gripper arm with self-locking joints developed by a dedicated student project group at Hochschule Esslingen, 3D-printed sealed buoyancy modules, and a PoE camera architecture replacing the 2025 USB design.

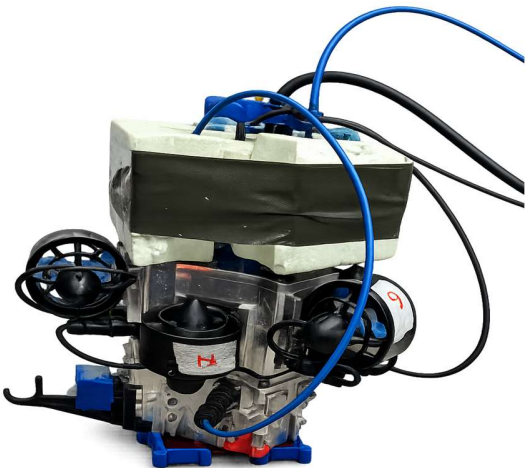


Figure 2 The ROV for this year

2.1 Vehicle Structure and Frame

Four subassemblies are stacked along the vertical axis: the buoyancy module (top), the Navigation Box, the Exploration Box, and a steel ballast plate (base). This arrangement maximises the vertical separation between the centre of buoyancy (CoB) and the centre of gravity (CoG), which drives passive roll and pitch stability. Both electronics boxes are CNC-machined from aluminium 5083. The Navigation Box was machined in-house on a 3-axis machine; the Exploration Box (deeper internal pocket geometry) was outsourced to a 5-axis machine shop. The two boxes are joined by the Common Birthing Adapter, which allows indexed rotation in 120° steps about the Z axis and carries CAN bus, Ethernet, and power.

Six BlueRobotics T200 thrusters are arranged in two sets of three, each set offset 60° relative to the other around the Z axis. The six-thruster triangular layout saves two thrusters compared with a conventional eight-thruster vectored design, reducing cost, mass, and footprint while

providing four directly controllable degrees of freedom (surge, sway, heave, yaw) plus active roll and pitch stabilisation via IMU-commanded differential thrust. For 2026 the 2025 chassis was refurbished and reused; a parallel two-year development path towards a new metal 3D-printed single-body chassis is ongoing.

Vehicle Dimensions and Mass

Parameter	Value
Length (X), without removable tools	340 mm
Length (X), with gripper arm extended (est.)	~750 mm
Width (Y)	340 mm
Height (Z)	420 mm
Mass in air	12.5 kg
Net buoyancy in fresh water	Slightly positive — verified by trim test

Material Selection

Material	Application	Selection Rationale
Al 5083	Chassis boxes and lids, Common Interface female parts, camera-housing end plates	Maritime alloy; 215 MPa yield strength; corrosion-resistant; good machinability.
ABS (FDM)	Common Interface male parts, camera housings, buoyancy module, gripper housings	Low cost; fast iteration; adequate strength after Dichtol sealing.
PLA (FDM)	Task-module brackets, prototypes	Lowest cost; high stiffness; dry-zone use only.
SLA resin	Servo motor housings	Dimensional precision; inherently watertight after post-cure.
PMMA (laser-cut)	Camera front windows, connector covers	Optically clear; low cost; suits flat laser-cut geometry.
S235JR steel	Ballast plate	High density (7,850 kg/m³) at low cost; maximises CoG lowering.
1.4404 stainless	Structural fasteners, gripper shafts	Marine-grade; corrosion-critical interfaces.
NBR 70	All static O-ring seals	Standard marine elastomer; broad temperature and chemical resistance.
Dichtol	Sealant for FDM structural parts	Liquid polymer; fills FDM porosity in 10 min soak + 24 h cure.

Structural Analysis

Both electronics boxes and the Common Interface were verified by finite element analysis (Fusion 360 Simulation) under a uniform pressure of 100 kPa — equivalent to 10 m depth. The minimum wall thickness of 4 mm (Navigation Box) and 5 mm (Exploration Box) yields a maximum Von Mises stress below 90 MPa in Al 5083 (yield 215 MPa), giving a safety factor exceeding 2.4 at the rated depth. O-ring grooves follow DIN 3771 geometry; Souriau UTSX connectors are torqued to the OEM torque specification.

2.2 Common Interface and Modularity

The Common Interface is the standardised mechanical and electrical coupling between the chassis and every module. A female part bolted to the chassis accepts a male part integrated into any module. Coupling is achieved by a single M5 bolt that draws the male into the female along two double-conical mating surfaces. The geometry is self-aligning, tolerates wide manufacturing tolerances, and accepts mixed-material pairings. Seven mounting positions are available on the vehicle; any module fits any position. The geometry is unchanged from 2025, maintaining full backward compatibility: a thruster or camera designed for the 2025 ROV fits the 2026 vehicle without modification. Any single module, including a failed thruster, can be replaced without affecting adjacent modules; a complete tool reconfiguration fits within one competition break.

Sealing Strategy

Three complementary approaches seal every boundary between the electronics volumes and the water:

- Static O-ring seals: three NBR 70 185 × 2 mm O-rings at the tub/sleeve/lid interfaces of each box. Mating surfaces finished to $R_z < 6.3\ \mu\text{m}$ and verified on as-machined parts.
- Bolt penetration seals: a bonded sealing washer under each bolt head crossing the sealed boundary, plus an NBR 70 9 × 2 mm O-ring around each Common Interface thread.
- Eaton Souriau UTSX flange receptacles: all cables terminated in-house to the manufacturer's torque specification. FDM structural parts sealed with Dichtol (10 min soak, 24 h cure, validated at 1 m for 72 h on test coupons).

Pressure Tests

Test Article	Depth	Duration	Result
Empty chassis — basic seal check	6 m	30 min	Pass
Chassis — shallow long soak	1 m	2 h	Pass
Chassis — IP28-equivalent	6 m	2 h	Pass
Dichtol FDM coupons (short)	1.5 m	15 min	Pass
Dichtol FDM coupons (long)	1 m	72 h	Pass
Silicone flange seal prototype	6 m	10 min	Pass (experimental)

2.3 Buoyancy and Ballast

The vehicle is trimmed for slight positive buoyancy, so any propulsion or control failure converts to a passive surface ascent without pilot input. The buoyancy module sits at the top of the chassis and the steel ballast plate at the base, maximising the CoB–CoG vertical separation and producing strong passive righting moments.

The 2026 buoyancy element is FDM-printed in PLA, sealed with Dichtol, and bolted to the Navigation Box lid via a Common Interface. Unlike the 2025 polystyrene block, which gradually saturates on long dives, the sealed FDM module maintains constant buoyancy. Its effective density is set by the infill pattern and is known a priori from the CAD model; additional modules can be stacked to adjust buoyancy without redesign. Trim was verified in the pool at the surface, 1 m, and 6 m depth by iterative addition or removal of ballast until the vehicle held

level throughout. Every task module is designed to an effective density of approximately 1.0 kg/L so the static buoyancy block remains sufficient across all tool configurations without in-mission adjustment.

2.4 Payload and Tools

Every tool in the 2026 configuration addresses at least one published mission task. All tools couple to the chassis via the Common Interface and can be swapped between Product Demonstration runs.

Tool	Primary Function	Addressed 2026 Mission Tasks
4-DOF gripper arm (new 2026)	4-DOF arm; self-locking joints; CAN-controlled	Tasks 1.1, 2 (eDNA swap, biofouling, acoustic-release)
Lifting hook — C-shape (2nd iteration)	Passive retrieval of corals, sensors and cap	Task 1.1 (backup); Task 2 pickup
Cable winch with hook	Deploy and recover fixed rope	Task 2 lobster-pot recovery
Camera array — Pi Cam V3 + Pi Zero PoE (new 2026)	Pilot navigation; manipulator view; photogrammetry	All tasks; Task 1.2 coral-garden 3D model

4-DOF Gripper Arm

The 2026 main manipulator is a four-DOF underwater arm developed at Hochschule Esslingen, replacing the three-servo 2025 design. A CAD audit of the previous arm identified and corrected three root-cause faults before manufacturing: incorrect gear centre distances, undersized O-ring grooves, and incorrect shaft-seal seats. J1 provides base yaw rotation, while J2 uses a self-locking worm gear to hold position without continuous current, reducing power consumption and preventing uncontrolled motion during power loss. J3 integrates pitch and continuous roll in a compact bevel-gear differential, and J4 actuates the claw via a digital servo. J1–J3 are driven by brushed DC motors with encoders for closed-loop control. Each joint contains an STM32F303K8T6 controller communicating via the shared CAN bus. The ABS FDM-printed housings target IP68+ sealing at 5 m depth. Overall dimensions are approximately 550 × 165 × 86 mm

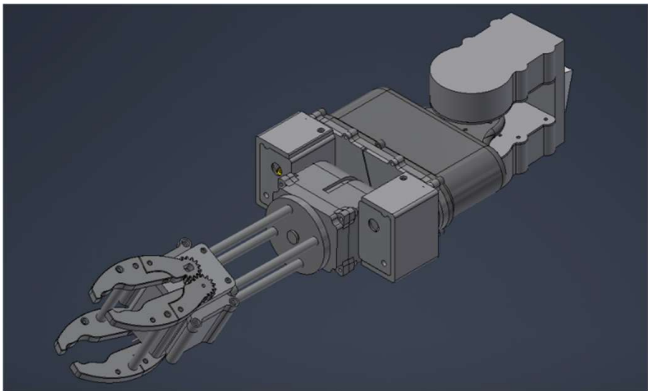


Figure 3 4-DOF Gripper Arm

Lifting Hook and Cable Winch

The lifting hook is a passive C-shaped tool for retrieving corals, sensors, and the sample cap. It is the second design iteration: the first straight 30 cm hook proved oversized and poorly controllable in pool tests. The C-shape is slimmer, easier to align in confined spaces, and tolerant of small pilot misalignment. The two-bolt bracket is unchanged, so the hook swaps without disturbing the adjacent camera. The cable winch is a drum-and-hook assembly for

deploying and recovering a fixed rope (Task 2 lobster-pot recovery). A tiered drum layout prevents rope tangling.

Camera Array

Three cameras are carried in the standard mission configuration, selected to provide pilot navigation sightlines, close-up manipulation view, and photogrammetric data coverage without exceeding the available PoE Souriau receptacles. The system architecture changed from USB (2025) to Power-over-Ethernet in 2026, using Raspberry Pi Camera Module 3 sensors paired with Raspberry Pi Zero 2 boards carrying PoE HATs. The Pi Cam V3 provides substantially higher image quality than the 2025 USB cameras, which is critical for the photogrammetric Task 1.2 deliverable. Camera placement was optimised by CAD simulation of field-of-view coverage and refined by pilot feedback in pool sessions.

Onboard Sensors

Sensor	Location	Interface	Specification	Mission Relevance
Pressure (depth)	Exploration Box	I ² C	0–300 kPa; ±0.25% FS	Depth reference for coral-garden survey (Task 1.2); buoyancy trim verification
Humidity / moisture	Exploration Box	I ² C	0–100% RH; ±2% RH	Micro-leak early warning before water reaches electronics
IMU: LSM6DSM + HMC5883L (accel, gyro, mag)	Navigation Box	I ² C	±8 g / ±2000°/s / ±8 Ga	Active roll/pitch stabilisation via differential thrust; pilot heading reference

2.5 Build vs. Buy and New vs. Reused

Parts whose geometry directly drives mission performance or sealing are designed and manufactured in-house (Common Interface, camera housings, task tools, buoyancy module, gripper housings, aluminium boxes). Commodity items where in-house manufacture adds no engineering value or carries unacceptable reliability risk are purchased: T200 thrusters, Basic ESCs, Pi Cam V3 modules, NBR 70 O-rings, Souriau connectors, brushed DC motors, STM32F303K8T6 gripper control boards, and the 48 V to 12 V DC/DC converter (an earlier in-house PCB attempt failed on design competence; risk minimisation outweighed volumetric efficiency). Year-over-year reuse: the 2025 chassis, T200 thrusters, ESCs, and Souriau connectors are reused after refurbishment and qualification re-test.

2.6 Manufacturing Processes

Process	Applied To
CNC milling — 3-axis, in-house	Navigation Box; Common Interface female parts; connector covers; camera-housing end plates; S235JR ballast plate.
CNC milling — 5-axis, outsourced	Exploration Box tub (deep single-clamp pocket geometry).
FDM 3D printing (ABS/PLA)	Common Interface male parts; camera housings; buoyancy module; task-module structures; gripper housings. Dichtol-sealed where required.

Process	Applied To
SLA 3D printing (resin)	Servo motor housings; PoE camera enclosure precision parts.
Laser cutting (PMMA)	Acrylic camera front windows; connector covers.

3. Electrical Subsystem

The electrical subsystem of the ROV has been substantially revised for the 2026 competition season. The key changes relative to the 2025 design are the transition from UART to CAN bus communication and the replacement of the USB-based camera system with a custom Ethernet-based camera solution. This section describes the power distribution architecture, motor control, tether design, communication protocols, camera system, sensors, and build-vs-buy decisions.

3.1 Power Distribution

The ROV operates across five voltage levels, each serving a distinct function. The 48 V supply provided by the MATE power supply is passed directly to the thruster unit without conversion, where it powers the DC-DC step-down converters that generate the lower voltage rails.

Voltage	Where Used	Max. Current	DC-DC Converter
48 V	Main supply line. Required by thruster unit for DC-DC converters (12 V and 5 V).	20 A	N/A (direct from MATE supply)
12 V	Secondary supply for ESCs in thruster unit and for accessory unit.	40 A	2× Generic 20–60 V → 12 V / 20 A step-down converter
5 V	Pi Pico in thruster unit; Raspberry Pi 5 and cameras in accessory unit.	6 A	Traco Power TDN 5WI — 12 V → 5 V step-down
3.3 V	GPIO pins of Pi Pico for ESC PWM control signals.	N/A	N/A (GPIO output)
±2.5 V	CAN bus differential voltage level.	N/A	N/A (CAN transceiver hardware)

3.2 Motor Controllers and ESCs

The six BlueRobotics T200 thrusters are driven by BlueRobotics Basic ESCs. Compared to the 2025 design, the primary change in the motor control subsystem is the GPIO pin assignment, which has been updated to accommodate the CAN bus interface. A Waveshare RP2350 CAN board replaces the Raspberry Pi Pico used in 2025 as the central motor controller, integrating a CAN controller directly on the microcontroller board and simplifying the hardware stack.

3.3 Tether Design and Communication

The tether consists of two separate cables: a power cable and a communication cable. The power cable uses two conductors (48 V and GND) with a cross-section of 2.5 mm² per conductor and no shielding. The communication cable is a standard CAT5 cable with a conductor cross-section of 0.51 mm².

CAT5 was selected for communication because 100Base-T Ethernet uses only four of the eight available conductors, leaving four conductors free. Two of these spare conductors are repurposed for the CAN bus differential pair (CAN HIGH and CAN LOW). This approach reduces cost and complexity by using a single, widely available, well-shielded cable for both Ethernet and CAN communication simultaneously. Tether buoyancy is achieved using small foam pool noodle segments attached at regular intervals along the tether — chosen for simplicity, low cost, and ease of integration.

3.4 Communication Protocol — UART to CAN

In 2025, UART was used as the communication protocol. While functional at the 15 m tether length used that year, UART proved unreliable at the 25 m tether planned for 2026. UART was originally adopted as a transitional solution under time pressure; its TTL signal specification is rated for only 1–3 m. For 2026, CAN bus has been adopted as the replacement protocol.

Aspect	UART	CAN
Topology	Peer-to-peer	Bus (multi-device)
Distance	Limited (TTL guideline: 1–3 m; 25 m tether caused signal issues)	Robust over long distances; time-critical packets arrive reliably
Hardware	No special hardware required	Requires dedicated CAN controller (e.g. Waveshare RP2350 CAN board)
Programming	Simple; quick to implement	More complex; higher development effort
Cost	Low	Higher (additional hardware)
Verdict	Transitional solution; used in 2025. Unsuitable for 25 m tether.	✓ Selected for 2026 — superior reliability, scalability, and noise immunity.

3.5 Camera System

The 2025 camera system used standard USB cameras connected to a Raspberry Pi 5, creating a processing bottleneck and delivering insufficient image quality for potential future computer vision use. For 2026, a custom Ethernet-based camera system has been developed. Each camera unit consists of a Raspberry Pi Zero 2 W, a Raspberry Pi Camera Module 3, a Waveshare PoE Ethernet HAT, and a custom-built waterproof housing. Power is delivered via PoE, and video streams are transmitted directly over the Ethernet network, eliminating the processing load on the main computer.

Three cameras are deployed on the ROV. Two cameras are mounted facing two of the three sides of the triangular frame, enabling the pilot to monitor tool operations from multiple angles. The third camera faces upward to assist with navigation back to the drop station.

3.6 Sensors

The IMU (gyroscope and magnetometer) is electrically integrated into the control board. Active sensor-based stabilisation and orientation feedback are partially implemented; refer to Section 2.4 (Onboard Sensors) for the full sensor table. A pressure sensor is planned for full depth-hold integration in a future iteration.

3.7 Tether Management Protocol

The tether is stored loosely coiled during transport and deployment. The Ethernet splitter and USB-CAN adapter are transported separately alongside the laptop in a dedicated bag. Marine-grade cables and reinforced Ethernet wiring improve resistance to water, abrasion, and repeated use. Strain relief points are installed on both the ROV and control box to reduce cable stress, while buoyancy foam sections keep the tether suspended and away from thrusters. During operation, a dedicated tether manager handles the tether by safely coiling, paying out, and retrieving cable as the ROV moves. This prevents excessive tension and reduces the risk of entanglement.

3.8 Leak Detection

No active electronic leak detection system is currently implemented on the ROV. Leakage is assessed manually by visual inspection after each run. In practice, any leak encountered falls into one of two categories: minor ingress that does not prevent completing a demonstration run, or severe ingress requiring retrieval and repair. An onboard humidity sensor provides early-warning capability before water reaches critical electronics. A valve-based leak detection mechanism is currently in development.

3.9 Build vs. Buy / New vs. Reused — Electrical

Component	Manufacturer / Model	Classification	Justification
ESCs	BlueRobotics Basic ESC	REUSED	Proven, reliable performance at small size and reasonable cost. No advantage in building in-house.
Thrusters	BlueRobotics T200	REUSED	Industry standard for competition ROVs. Same rationale as ESCs; re-verified in 2026 sealing tests.
Camera System	RPi Zero 2 W + Pi Camera 3 + Waveshare PoE HAT + custom housing	BUILT	2025 USB cameras had insufficient quality for potential AI use. Commercial IP cameras are too large or expensive. Custom design meets all requirements.
Gripper Control	STM32F303K8T6 per joint, custom CAN integration	BUILT	Distributed CAN architecture required; no off-the-shelf board with the correct form factor and integration existed.
DC/DC Converter (48 V → 12 V)	Generic 20–60 V / 20 A step-down module	PURCHASED	In-house PCB attempt failed. Risk minimisation outweighed volumetric efficiency.
DC/DC Converter (12 V → 5 V)	Traco Power TDN 5WI	PURCHASED	Proven industrial quality; cost-effective at the required current level.

4. Software Subsystem

For the ROV's software, the team built a Master/Slave control system that connects the desktop pilot interface to the embedded hardware. The primary goal was to reliably translate high-level pilot inputs into low-level motor thrusts in real-time, using an asynchronous command-and-response setup over a CAN bus. This keeps telemetry and state synchronisation robust without lagging pilot controls.

4.1 Architecture, Modularity, and Design Rationale

The team chose a highly modular, decoupled architecture for three key reasons. First, fault isolation: by separating the GUI (Master) from the hardware control logic (Slave), a crash on the surface PC does not crash the ROV — the Pico maintains its last known safe state or gracefully shuts down thrusters. Second, parallel development: the modular structure allowed the software team to work simultaneously, with one group focused on the C# WPF UI and another on MicroPython hardware drivers, connected only by an agreed-upon CAN dictionary. Third, deterministic execution: by offloading complex UI rendering and network handling to the PC, the Raspberry Pi Pico dedicates 100% of its resources to computing the 6-DoF matrix and pulsing the ESCs, guaranteeing low-latency response times.

Communication uses a simple offset addressing schema: the PC sends commands on a Base ID, and the Pico replies on Base ID + 1. The system initialisation follows a strict handshake: the PC sends an InitConnection frame (ID 50), the Pico acknowledges with ID 51, the PC sends InitThrusters (ID 60), and the Pico starts sending 50 Hz PWM signals to the ESCs and replies with ID 61, confirming the ROV is armed.

4.2 LCE — Master Control Engine and System State Machine

The Local Control Engine (LCE) handles thrust allocation and power management. The microcontroller runs a non-blocking control loop split into a 1 Hz status loop and a 10 Hz hardware keep-alive loop. The ROV boots into a Wait State (0), preventing accidental thruster spin-up until the GUI explicitly authenticates and initialises the system into Normal Operation (1). Any hardware failure forces an Error State (2). LED blink rates provide physical visual feedback to deck crew for each state.

The trickiest part of the LCE is processing the 6-Degrees of Freedom (6-DoF) mixing matrix. Writing configuration data to the Pico's flash memory momentarily freezes CPU execution; a flash memory debouncing mechanism using software locks (`_is_saving`) holds incoming directional values in RAM, only writing to flash once all six parameters arrive. This prevents CPU lockup during active pilot control. A custom SPI CAN driver runs the SPI clock at 10 MHz, using a falling-edge hardware interrupt rather than polling to minimise latency.

4.3 GUI, Operator Performance, and Mission Task Relations

The team transitioned from Windows Forms to WPF using the MVVM design pattern to significantly improve UI maintainability. Software requirements are mapped directly to the 2026 Mission Tasks to optimise pilot performance.

- Mission Task - Precise Infrastructure Manipulation: Dynamic throttle scaling (`ApplyControllerValues_Dyn` CAN command) allows the pilot to instantly cut the global thrust multiplier via the GUI, enabling micro-adjustments during fine-manipulation tasks.
- Mission Task - Visual Observation and Identification: A startup routine grabs screen metrics and locks the GUI window to the right half of the pilot's monitor, reserving the left side for external camera feeds and preventing window drift on restart.
- Deck-Side Debugging: A Direct Hardware Override command (ID 170) allows the crew to bypass the mixing matrix and send raw PWM bytes directly to a specific thruster, saving time during pre-dive checks.

4.4 Development Process and Quality Assurance

The team relies on a strict Git branching strategy and Hardware-in-the-Loop (HIL) testing, running code directly on the physical ROV. Key fail-safes include serial framing with start/end byte validation (0xAA / 0x55) to discard corrupt frames without buffer desync; a high-resolution stopwatch measuring round-trip latency from serial port to CAN bus and back (timeout at 500 ms to ensure stable flight); and a CAN Loopback Diagnostic mode that broadcasts a dummy payload every 500 ms to test SPI hardware independently of the state machine.

4.5 Artificial Intelligence as a Development Tool

In alignment with modern software engineering practices, the team utilised AI (specifically GitHub Copilot and Large Language Models) as an efficiency multiplier and educational tool. AI was used to explain complex datasheet registers for the XL2515 CAN controller, to generate boilerplate C# structures for the MVVM implementation, and to help debug byte-shifting errors in C#-to-Python payload serialisation. All architectural decisions, system designs, hardware-in-the-loop testing, and final logic implementation were executed by the student team.

5. Non-ROV Device — Autonomous Profiling Float

5.1 Physical Structure

Total length: 620 mm (62 cm).
Maximum outer diameter: 165 mm (16.5 cm). Total weight: approximately 7.2 kg. The main body consists of a polymethyl methacrylate (PMMA) tube with turned aluminium end caps. An internal platform-based structure houses the electrical devices, motor, power supply, and buoyancy engine. A ballast container is attached to the bottom end cap; the top end cap houses a ball valve and a Wi-Fi antenna.

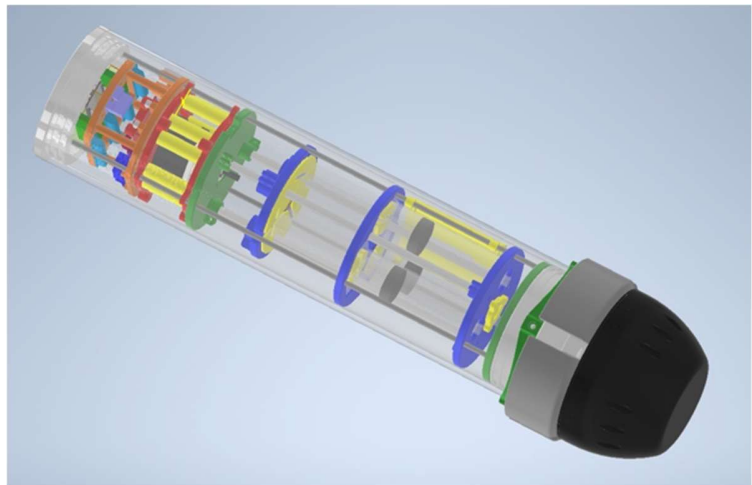


Figure 4 The Float

Waterproofing: two O-ring seals on each end cap. The top ball valve allows connection to a vacuum pump before diving to create slight internal negative pressure, ensuring end caps remain seated during surface handling before external hydrostatic pressure forces them shut at depth. Hull penetrations are strictly limited to the buoyancy engine inlet/outlet hoses.

5.2 Buoyancy Engine Mechanism

Core mechanism: syringe-based volume displacement. A stepper motor connected to a planetary gear with a 5:1 reduction ratio drives a spindle connected to the syringe heads. To ensure sufficient torque to overcome high external hydrostatic pressure at maximum depth without stalling, the buoyancy engine uses a 2-syringe array for drawing in water.

5.3 Communication Protocol and Lossless Data Guarantee

The core controller is an onboard ESP32 microcontroller connected to a waterproof top-mounted Wi-Fi antenna. Because radio frequencies do not penetrate water, the Wi-Fi connection is lost upon submergence. The ESP32 autonomously collects and logs all measurement data to onboard memory during the dive. Once the float completes its profile and the antenna breaches the surface, Wi-Fi automatically reconnects and users download complete log files from the onboard webserver. Pressure and depth are displayed graphically and in table form.

5.4 Vertical Profile Mission Operations

Pre-Dive: operators connect to the ESP32 webserver to set target pressure, calibrate buoyancy, adjust PID parameters, set the dataset name, and initiate the dive sequence. A Balluff relative pressure sensor in the lower end cap measures external water pressure; an internal pressure sensor provides the baseline reference and dynamically compensates for initial vacuum and temperature-induced internal pressure changes. The control system calculates actual depth by comparing external and internal pressure and drives the stepper motor to adjust buoyancy, reaching target depth stops, collecting data, and resurfacing.

5.5 Electrical System and Power Budget

Parameter	Value
Battery	12 V NiMH pack — 10 cells in series, ring configuration
Total capacity	2,200 mAh
Cable cross-section (power lines)	0.75 mm ²
Protection	1 A inline fuse on main circuit
Idle current (all systems active)	250 mA
Continuous current (buoyancy engine active)	330 mA
Peak current (stepper motor startup)	550 mA
Theoretical maximum runtime (at 330 mA)	~6.6 h

Safety features: hardwired limit switches at upper and lower track extremes prevent buoyancy engine over-extension. An internal humidity and temperature sensor detects potential seal breaches. A magnetic reed switch serves as the main power toggle, activated by an adjustable magnetic ring on the outside hull to prevent additional hull penetrations.

6. Critical Analysis — Testing and Troubleshooting

This section documents the 2026 testing methodology, troubleshooting strategy and fault trees, three documented build-season case studies, key trade-off decisions, and the failure-mode analysis informing safe in-water operation.

6.1 Vehicle Testing Methodology

Testing follows a three-layer structure: component-level bench tests, full-system pool integration tests, and real-time signal-path fault finding during operation. A hardware-in-the-loop (HIL) bench for the thruster signal chain (CAN bus to Pi Pico to ESC to T200) allows firmware changes to be regression-tested on the bench before pool deployment. The gripper arm underwent its own component-level campaign: leak tests, underwater grip tests, CAN-bus communication tests, and PID loop tuning.

Date	Session	Primary Purpose
25.04.2026	Regional competition	First full-mission deployment under judged conditions
12.05.2026	Qualifier video — pre-shoot	Software validation after CAN-bus conversion
13.05.2026	Qualifier video — main shoot	Competition qualifier recording
15.05.2026	Qualifier video — follow-up	Re-shoots and pilot training

6.2 Prototyping to Evaluate Design Options

Every mechanically complex component is first prototyped in FDM PLA before committing to CNC machining or a final design. For the 2026 chassis, a full-scale PLA prototype verified hole and thread positions, Souriau connector mounting, electronics layout, and Common Interface mating before aluminium was ordered. The prototypes also supported design reviews with machining staff, enabling CAD corrections before manufacturing. For the camera housing, testing showed the lens contacted the acrylic front window under vibration, leading to the addition of a spacer before production. The gripper arm redesign was prototyped entirely in CAD. A detailed audit of the 2025 model identified and corrected three root-cause faults before any 2026 parts were printed, avoiding a failed physical assembly at minimal cost.

6.3 Troubleshooting Strategy

All troubleshooting follows the signal path from the surface operator down to the actuator. Each path is mapped into a fault tree per subsystem, with every node testable by a multimeter, oscilloscope, or a named software checkpoint in the LCE. The LCE exposes checkpoints for raw gamepad input, the processed DoF target vector, calculated PWM targets, and every CAN write attempt. In most fault scenarios, the operator isolates the fault to a specific node before any physical disassembly is required.

Thruster / Steering Fault Tree

Step	Component Under Test	Test Method
1	Xbox controller	Gamepad test software on surface laptop
2	LCE control engine	Console checkpoint: raw DoF input and processed thrust command
3	CAN-to-USB adapter (surface)	Multimeter on CAN line resistance; adapter status LED
4	CAN breakout PCB on tether	Multimeter continuity
5	Tether CAN conductors	Multimeter end-to-end continuity
6	Pi Pico in Navigation Box	Direct USB connection from laptop; console output

Step	Component Under Test	Test Method
7	ESC	Move ESC to known-good Pico pin; run ramp script; check supply voltage

Camera Fault Tree

Step	Component Under Test	Test Method
1	Camera module	Disconnect from vehicle; connect directly to laptop
2	Raspberry Pi 5 in Exploration Box	SSH remote connection; check camera device list
3	Exploration-to-Navigation Box link	Multimeter continuity on Ethernet and power conductors
4	Tether Ethernet conductors	Multimeter end-to-end continuity
5	Surface GUI camera pipeline	Check stream rendering in the GUI display panel

Gripper Fault Tree

Step	Component Under Test	Test Method
1	Xbox controller / keyboard input	Gamepad / keyboard test software
2	LCE gripper command output	Console checkpoint: gripper CAN write attempts
3	CAN-to-USB adapter (surface)	Multimeter; status LED
4	CAN breakout PCB on tether	Multimeter continuity
5	Tether CAN conductors	Multimeter continuity
6	Inter-box cable	Multimeter continuity
7	STM32 control board in affected joint (J1–J4)	CAN address ping; on-board LED; motor supply voltage

6.4 Documented Troubleshooting Case Studies

Case 1 — PWM Pin Mis-Assignment on Revised Pi Pico

Before the qualifier video shoot, two thrusters were unresponsive. Testing showed the fault originated from the Pi Pico PWM outputs rather than the ESCs. The issue was traced to changed PWM pin assignments after a CAN-bus firmware update. The PWM lines were re-soldered to match the new pinout, and a corrected PCB was later installed. As a preventive measure, PWM pin maps are now version-controlled and reviewed with every PCB revision.

Case 2 — Control Errors After CAN-Bus Software Update

Following the CAN-bus migration, the vehicle responded incorrectly to pilot inputs during the Regional competition. Hardware and controller input tests confirmed the fault lay in the thrust-allocation software. A vector-calculation error introduced during the update was identified and

corrected, then verified in the next pool test. This led to the creation of a HIL test bench to enable unit testing of thrust-allocation functions before deployment.

Case 3 — CAN Short Circuit on Inter-Box Cable

On qualifier video day, the CAN bus failed after transport to the pool, although pre-departure checks were successful. Measurements and sequential disconnection isolated the fault to the inter-box cable, where inadequate insulation allowed conductors to short during transport vibration. A field repair using insulation tape restored operation in time for the shoot. Preventive actions included stricter insulation QC, added strain relief, and CAN resistance checks in the pre-departure procedure.

6.5 Key Trade-Off Decisions

Decision	Options Compared	Outcome and Reasoning
Manipulator architecture	3-servo arm (2025) vs. 4-DOF worm-gear arm (2026)	4-DOF arm selected. Worm gears at J2 are self-locking, eliminating holding current. Bevel differential at J3 collapses two axes into one housing.
Gripper control bus	Centralised PWM bundle (2025) vs. distributed STM32 boards on CAN (2026)	Distributed CAN. Eliminates per-tool PWM cable bundle; shares thruster diagnostics; scales to additional joints without added surface cabling.
Camera architecture	USB cameras (2025) vs. PoE Ethernet (Pi Cam V3 + Pi Zero, 2026)	PoE Ethernet selected. Higher image quality for photogrammetry; lower latency; no additional tether conductors. USB cameras retained as fallback.
48 V → 12 V DC/DC converter	In-house PCB design vs. purchased commercial module	Purchased. Earlier in-house attempt failed on PCB design competence. Risk minimisation outweighed volumetric efficiency.
Buoyancy material	Polystyrene block (2025)	Polystyrene is cheap and easy to use

6.6 Failure-Mode Analysis

Positive buoyancy trim is the primary passive safety property: any propulsion or control failure converts to a surface ascent without pilot input.

Failure Mode	Expected Vehicle Behaviour	Recovery
Software crash on surface laptop	ROV stops responding; positive buoyancy carries vehicle to surface.	Recover via tether; restart surface software.
Tether breakage	Vehicle surfaces under its own buoyancy.	Surface recovery. Negative trim is explicitly avoided for this reason.
Water ingress — Exploration Box	Cameras fail; humidity sensor alarm fires. Pilot drives blind to surface using IMU heading and tether tension.	Tether-assisted ascent; dry and service Exploration Box.
Water ingress — Navigation Box	Thruster control may fail; humidity sensor gives early warning before full failure.	Tether retrieval; passive positive buoyancy provides backup ascent.

Failure Mode	Expected Vehicle Behaviour	Recovery
Single thruster failure	Loss of one DOF or one stabilisation axis; ROV remains driveable in degraded mode.	Recover; replace thruster via Common Interface (target: 60 s); re-test.
Single gripper joint failure (J1–J4)	Affected DOF lost; remaining joints under closed-loop control; worm gear at J2 holds last commanded position without power.	Continue mission in degraded mode; service joint between runs.

7. Safety

At U.Stall, safety is a core part of team culture. Technical excellence is only meaningful when paired with responsible, safe practices—both in the lab and during field operations. A dedicated Safety Officer oversees enforcement and ensures that both the construction and operations checklists are completed and signed before any major build step or deployment.

Safety Philosophy

Within the U.Stall framework, safety protocols are established across three primary pillars: **Personnel** (encompassing laboratory discipline and personal protection), **Equipment** (the preservation of modular hardware and sensitive electronics), and **Operations** (the execution of standardized, monitored deployment cycles)..

7.1 Safety Rationale & Precautions

Personnel Discipline:

Safety protocols mandate the use of closed-toe footwear, tight-fitting laboratory attire, and secured hair, with first aid and fire suppression equipment maintained in a state of immediate readiness. During field operations, stable footing or dual-person monitoring is required at the water's edge.

Equipment Preservation: Electrical circuits are protected by 20 A fuses to mitigate thermal risk. Every watertight volume undergoes a 1 m dry-run pressure qualification utilizing internal moisture-indicator media to validate seal integrity before full deployment. Tensile loads are managed by dedicated mechanical strain reliefs on the tether and Souriau interfaces to prevent ingress.

Operational Safety: Standardized protocols require two-person supervision for all powered states, initiated by a verbal warning to the deck crew. Hard copies of the operational and de-energizing procedures are maintained at the control station for reference during all mission cycles.

7.2 Vehicle-Specific Safety Features

Integrated Thruster Shrouds: Protective guards are installed on every T200 unit to mitigate the risk of physical interaction with propellers during deployment and mission cycles.

Manual Power Interrupt: Standardized Anderson Powerpole interfaces function as the primary toolless disconnect for the main circuit.

Passive Ascent Trim: The vehicle is calibrated for slight positive buoyancy, facilitating an autonomous surface recovery should a total system failure occur.

Kinematic Self-Locking: A worm-gear stage at joint J2 ensures the manipulator maintains its mechanical orientation without continuous current draw, even upon power loss.

Edge Conditioning: All CNC-machined aluminium sub-assemblies undergo a comprehensive deburring process prior to integration to eliminate sharp surfaces.

7.3 Safety Checklists

To ensure rigorous adherence to safety standards, U.Stall implements formalized verification cycles across the manufacturing and deployment stages. The operational checklists utilized by our team are appended to this technical documentation.

8. System Integration Diagram (SID)

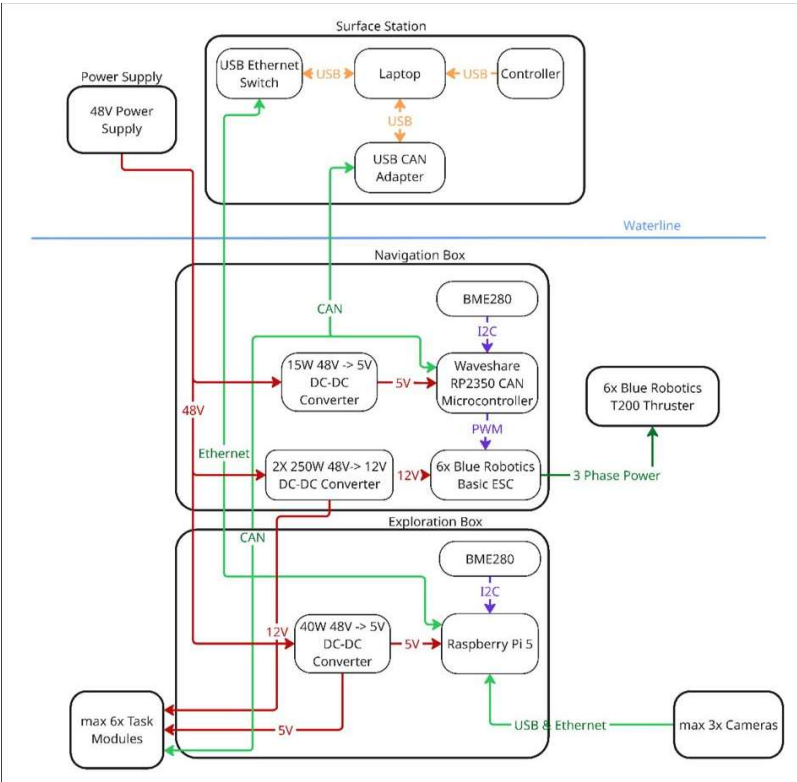


Figure 5 SID

9. Accounting and Budget

9.1 Budget Overview

Category	Description	Projected Cost (USD)	Actual Cost (USD)
Mechanical	machining, 3D printing materials,	4500USD	4.390 USD
Electrical / Electronics	ESCs, Pi boards, PoE HATs, connectors, cables	6500 USD	6.780 USD

Category	Description	Projected Cost (USD)	Actual Cost (USD)
Float Device	PMMA tube, AI end caps, ESP32, sensors, motor	800 USD	665 USD
Travel	Transport, accommodation for Regional and World Championship	15.000 USD	19.620 USD
General	e.g. O-rings, miscellaneous	7.000 USD	6.167 USD
TOTAL		33800 USD	37.262 USD

9.2 Project Costing — Detailed Component List

Item	Category	Vendor	Cost	Cost	Status	Donor (if donated)
Custom PCBs — PDU, TCU, motor driver boards (manufacturing)	Electrical	AISLER B.V.	1.000	\$1.090	Donated	AISLER B.V. (in-kind, contract 21.10.2026)
PCB components: connectors, regulators, MCUs, passives	Electrical	Mouser, RS, Eckstein, DigiKey	1.660	\$1.809	Purchased	—
Onboard hardware: Raspberry Pi 5C1110 x2, DC/DC modules	Electrical	BerryBase, Mouser, RS	1290	\$316	Purchased	—
Secondary sensors: Bosch BMP581, HDC3022, MS5837 x 4	Electrical	DigiKey (10/2025)	170	\$76	Purchased	—
Industrial pressure & temperature sensors	Electrical	Endress+Hauser Conducta	1.000	\$1.090	Reused	Endress+Hauser Conducts (2024 in-kind, still installed)
Thrusters & ESCs — 6 x Blue Robotics T200	Electrical	Blue Robotics	1.800	\$1.962	Reused	—
Tether & connectors — Souriau UTS, CAT5e	Electrical	Souriau, RS Components	400	\$436	Reused	—
Frame / chassis — Aluminium 5083 plates and brackets	Mechanical	Mädler, Stahl-shop24	450	\$491	Purchased	—
3D-printed mounts and jigs (PETG / PLA / Resin)	Mechanical	FD3D, filamentworld	1250	\$273	Purchased	—
Machined Polystyrol housings	Mechanical	3D-Form Winterbach	12.190	\$2.387	Reused	—
Waterproofing — O-rings, Wellendichtringe	Mechanical	123Kugellager, Techniparts	1290	\$316	Purchased	—
Manipulators — Feetech STS3215, Reely DT5022MG servos	Mechanical	Conrad, Eckstein, Mouser	1290	\$316	Purchased	—
Raw material — steel sheet, aluminium stock, plastics	Mechanical	Mädler, Kunststoffplatten	1250	\$273	Purchased	—
Float housing — tube, O-rings, fasteners, connectors	Float	various (legacy stock)	1360	\$392	Reused	—
Float electronics — motor, battery, depth sensor	Float	Pololu, DigiKey	1250	\$273	Purchased	—
Onboard cameras (USB / IP modules)	Cameras	various (legacy)	1300	\$327	Reused	—
Camera lenses, dome housings	Cameras	KAMERA	165	\$71	Purchased	—
GitHub Pro repositories (12-month equivalent)	Software	GitHub Inc.	150	\$55	Donated	GitHub for Education (educational grant)
Autodesk Fusion 360 — 11 educational seats	Software	Autodesk	1600	\$654	Donated	Autodesk Education programme
KiCad EDA suite	Software	KiCad project	-	-	Donated	Open source (recognised at zero FMV)
Pool time — Tauchsportcenter Esslingen (~10 sessions)	Operations	Tauchsportcenter Esslingen e.V.	1800	\$872	Purchased	—
PPE — workwear, safety glasses, gloves	Operations	Engelbert Strauss	440	\$480	Purchased	—
Marketing — shirts, banners, flyers	Operations	MC-Textildruck, CHS, T. Hohner	1900	\$981	Purchased	—
Internal document printing	Operations	HSE in-house print	190	\$98	Purchased	—
MATE Explorer registration + Fluid Power Quiz	Competition	MATE Center	1690	\$752	Purchased	—
Tech Documentation + Marketing Display printing for venue	Competition	HSE print + external	1200	\$218	Purchased	—
Flights — 7 team members, round-trip DE — YYT	Travel	DER Reisebüro	110.500	\$11.445	Purchased	—
Lodging — St. John's, 6 nights	Travel	Hotel TBD	15.000	\$5.450	Purchased	—
Ground transport — airport transfers, local	Travel	various	1.000	\$1.090	Purchased	—
Team meals during competition	Travel	various	1.500	\$1.635	Purchased	—
ROV shipment + Carnet ATA (air freight, customs)	Logistics	freight TBD, IHK Stuttgart Carnet	1.500	\$1.635	Purchased	—
TOTAL COST (Purchased + Reused + Donated, at FMV)			134.185	\$37.262	FX 1.09 @ 05.05.2026	

Subtotals by Status	
Purchased	
Reused	
Donated	

126.485	\$28.869
16.050	\$6.595
1.650	\$1.799

9.3 Income and Donations

Sponsor	Type of contribution	Net value (EUR)	Net value (USD)
ANDRITZ Schuler GmbH	Cash	€20.000	\$ 23.600,00
Richard-Gottschalk-Stiftung	Cash	€10.000	\$ 11.800,00
VDF Hochschulförderung	Cash	€3.000	\$ 3.540,00
Anton & Clara Röser Stiftung	Cash	€2.500	\$ 2.950,00
Endress+Hauser Conducta	Cash + in-kind	€2.500	\$ 2.950,00

9.4 Acknowledgements

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Finally, we thank the pool operators at Cityworks Göppingen and the Community of Jebenhausen for enabling safe underwater testing.

Appendix A — References

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4 TRACO Power. TDN 5WI Series 5 Watt DC/DC Converters Datasheet. TRACO Electronic AG; 2021. Accessed May 16, 2026. <https://www.tracopower.com>

5 Autodesk. Autodesk Fusion Simulation and Finite Element Analysis (FEA) Product Documentation. Autodesk; 2026. Accessed May 16, 2026. <http://help.autodesk.com>

Appendix B — ROV Construction Safety Checklist

This checklist must be completed and signed before any major build step. Both the acting person and a reviewing person must sign.

Electrical

- All cable connections insulated, no exposed conductors visible
- Fuses correctly dimensioned and installed
- Anderson Powerpole connectors correctly crimped and secured
- Main switch functional
- Voltage test conducted prior to initial power-up

Mechanical

- Thruster guards mounted and secured
- No sharp edges or protruding parts
- All screws and connections tightened
- Manipulator tested for correct function

Pressure Vessel / Watertightness

- O-rings intact and correctly seated
- Cable penetrators sealed
- Pressure test conducted

Buoyancy

- ROV trimmed to neutral or slightly positive buoyancy
- Ballast firmly mounted and secured

Tether

- Strain relief mounted
- No visible damage to the tether

General

- Workspace clean and dry
- Four-eyes check completed

Date and Time: [_____]

Name of Acting Person (legible): [_____]

Signature of Acting Person: [_____]

Name of Reviewing Person (legible): [_____]

Signature of Reviewing Person: [_____]

Appendix C — Operations Safety Checklist (JSEA)

Arrival / Preparation at Deployment Site

- Lift together when carrying heavy items and wear protective PPE
- Pack equipment securely so nothing hangs loose
- Place equipment only in designated areas
- Cover/secure all cables before switching on power
- Toolbox talk performed

Setup and Operational Procedures

- Always pull the tether at the strain relief point
- Coil tether properly and feed out efficiently
- Walk carefully (slip hazard) and watch the tether
- Ensure safe footing at the water's edge and confirm swimming ability
- When working at or in the water, stand or lie securely (have a second person assist if needed)
- Keep written operational and procedural plan available
- Ensure clear communication during operations (practice procedures)
- Check for open connectors and verify correct seating of all seals
- Handle Souriau connectors carefully (do not kink or pull cables)
- Verify that all thrusters are fitted with propeller guards

Powering Up Systems

- Ensure Anderson Powerpole connector is correctly seated
- Keep tether, hair, and accessories away from or secured against the ROV
- Wear tight-fitting clothing and closed-toe shoes

End of Deployment

- Fully de-energize the system before disassembly
- Follow the written disassembly plan
- Watch out for potential pressure build-up in the float

Date and Time: [_____]

Name of Safety Officer (legible): [_____]

Signature of Safety Officer: [_____]