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Scalable and Modular robotic tools for pipeline inspection and repair



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REPORT ON TUBERS PERFORMANCE ASSESSMENT

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1 Introduction

TUBERS (Scalable and Modular robotic tools for pipeline inspection and repair, GA 101070115, September 2022 – August 2026) set out to inspect and repair drinking-water mains from the inside, without excavation. About 20 % of treated water is lost in EU distribution networks, and each cubic metre lost carries 0.5 kWh of energy and 0.25 kg of CO₂ [GA, Part B]. The hard part is rarely the leak itself but reaching it: mains run beneath homes, roads and railways, where digging is disruptive, costly or not permitted. TUBERS introduces a new paradigm in minimally invasive inspection and maintenance in pipeline networks and water infrastructure.

This deliverable reports Task 8.3, *Evaluation of system performance*. It assesses the integrated system against the objectives and KPIs of the Grant Agreement (Part B, Table 1) and the functional requirements of Task 3.1, documented in D3.1 *Functional Requirements and System Architecture*. It is the written companion to D8.3 *Validated TUBERS prototype*, the video record of the final demonstration. In this report, each subsystem is evaluated as an independent component in Section 2, and in Section 3 the evaluation of the end-to-end system is reported in two stages: i) A preliminary testing round of the TUBERS system that took place in the facilities of VITENS during November 2025 in the Netherlands to receive early feedback on the system performance and drive the development leading up to ii) the final demonstration workshop that took place in Bendabl facilities in Athens during July 2026 where the complete end-to-end system was demonstrated and evaluated.

1.1 From the proposal to the final system

The proposal combined four technologies: a resident snake-like robot for long-distance travel (WP4), a modular soft robot with inchworm locomotion for inspection and repair (WP5), a coded-excitation ultrasonic inspection system (WP6) and a decision support system (DSS) driven by explainable machine learning (WP7). Fully integrated submerged testing in M35 showed that the snake-like platform could not be made reliably watertight within the remaining time and budget. Following the RP2 review (July 2025), the consortium consolidated behind the technologies carrying end-user value. The final system is a **dual soft-robot ecosystem** built on top of the modular architecture developed by Bendabl. The consortium tested an inspection version of the soft robot and a repair version of the soft robot built from one modular platform, both feeding into the horizontal DSS (Figure 1). The snake-like robot's architecture, navigation stack, simulation environment and interfaces are retained as an exploitable asset.

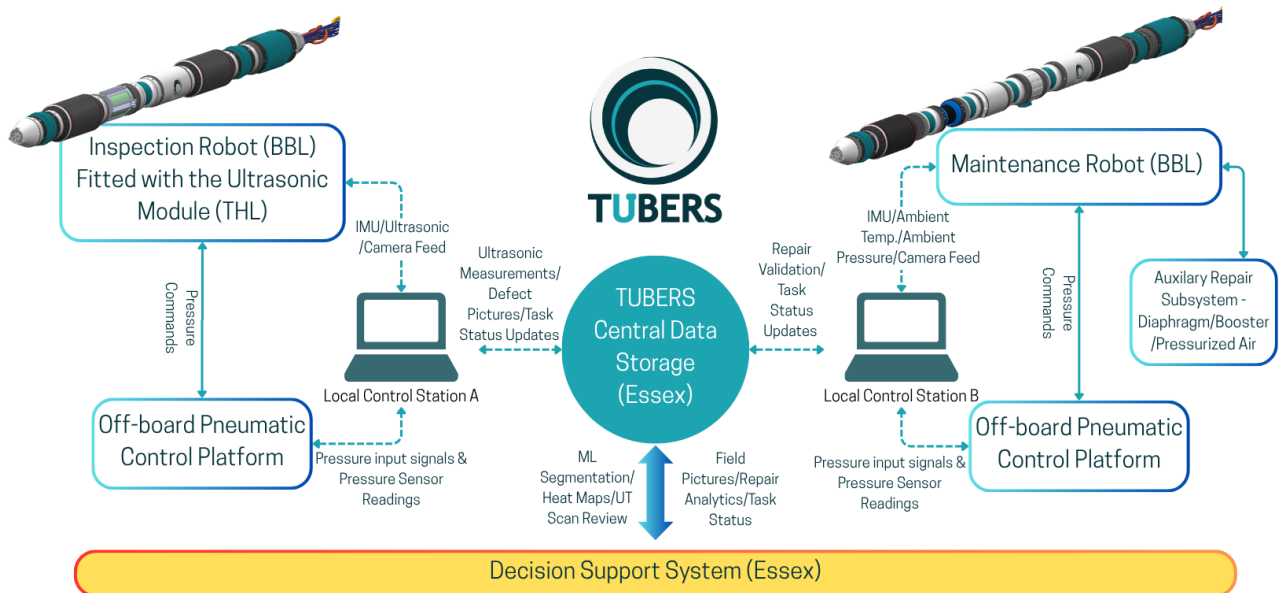


Figure 1: Final TUBERS architecture: two soft robots exchanging data and tasks through one decision support system

1.2 Planned work in WP8

WP8 *System Integration and Validation in field trials* runs from M27 to M48 under the lead of ALS. Its objectives are to implement TUBERS in an industrial setting, validate its ease-of-use and reliability, and identify areas of improvement (Table 1).

Table 1: WP8 tasks

Task	Leader (contributors)	Scope	Months
T8.1 Mechanical, hardware and software integration	DMC (BBL, THL, ALS, UESS)	Integrate hardware, sensors and software; verify the platform in a controlled environment	M13-M34
T8.2 System deployment on mock-ups and real conditions	ALS (all)	Staged deployment: in-house mock-ups → large-scale facility → live networks	M27-M48
T8.3 Evaluation of system performance	EVW (BRW, VIT, ALS)	Assessment against the T3.1 functional requirements: ease-of-use, success rate of each step, repair quality	M33-M48

The GA foresaw three validation stages. Table 2 maps them to what was executed, detailing what each round of testing included.

Table 2: Planned versus executed validation stages

GA stage	Executed	Reported in
1. Mock-ups at DMC and BBL	In-house mock-ups at BBL: parallel testing during development in mock-up pipe testbeds; snake-like robot at DMC, dry network	D4.1/D4.2/ D4.3/D5.1/ D5.2/D5.3
2. Large-scale facility	Preliminary demonstration at the Vitens facility (NL), Nov 2025, on a test network of industrial components	D8.2/D8.3
3. Live drinking-water networks	Carried out on the final demonstration at the Bendabl test facility, Jul 2026, on a water-filled, non-pressurised TRL 6 test bed built from utility-supplied components.	D8.2/D8.3

1.3 KPIs and assessment families

The GA defines seven objectives with measurable targets (Table 3). To make the verdict readable for non-specialists, the KPIs are grouped into five families: **Mobility** (where the robots can go and how fast), **Inspection** (what they can detect), **Decision** (how reliably defects are classified and repairs planned), **Repair** (how fast and how large a leak can be sealed) and **Deployment** (distance, trained people, open data). The same KPI IDs are used in §3.2.5 and §4. The project aims to raise the technology from TRL 4–5 to **TRL 6** by M48.

Table 3: Grant Agreement objectives and KPI targets (Part B, Table 1)

ID	Objective (WP)	KPI	Target	Family	Status
K1.1	1. Snake-like robot and navigation (WP4)	Traversal speed	4 m/min	Mobility	Partially Achieved
K1.2		Localisation accuracy	98 %	Mobility	Not Assessed
K2.1	2. Soft robot: locomotion, suction, repair (WP5)	Pipe width range	15–30 cm	Mobility	Achieved
K2.2		Repair deployment time	6 min/leak	Repair	Achieved
K2.3		Maximum leak size repaired	2 cm length	Repair	Achieved
K2.4		Traversal speed	1 m/min	Mobility	Achieved
K3.1	3. Ultrasonic inspection (WP6)	Minimum defect size detected	0.5 cm ²	Inspection	Achieved
K3.2		Minimum leakage detected	5 L/min	Inspection	Achieved
K4.1	4. Explainable ML and LCA/LCCA DSS (WP7)	False positives	< 10 %	Decision	Achieved
K4.2		False negatives	< 10 %	Decision	Achieved
K4.3		Holistic maintenance planning	Risk, LCA, LCCA modules	Decision	Achieved
K5.1	5. Validation in a real setting (WP8)	Cumulative length traversed in mock-ups	> 3 km	Deployment	Re-Scoped
K5.2		Length traversed in a live network	> 1 km	Deployment	Partially Achieved
K6.1	6. Training of deployment personnel (WP3)	Training workshops	2	Deployment	Achieved
K6.2		People trained	> 50	Deployment	Achieved
K7.1	7. Open data (WP2)	Data repositories (visual, ultrasound)	2	Deployment	Achieved
K7.2		Entries per repository	> 1000	Deployment	Partially Achieved

2. Subsystems Evaluation

2.1 Snake-like Robot

The resident snake-like robot (WP4, DMC) was designed for long-distance, autonomous travel through drinking-water mains, carrying the visual and ultrasonic payloads. By M48 it delivered a complete mechatronic architecture, a 20 m tether system, a navigation stack with its simulation environment, and verified interfaces to the UT module and to the Central Data Storage (Table 4).

Table 4: Snake-like robot capabilities demonstrated at M48

Demonstrated capability	Evidence	Next step
Locomotion through pipe segments and manoeuvring through junctions and obstacles	Miniature test network of significant complexity (DMC)	Robustness to rust, murky water, lens fouling, sediments and air pockets
Autonomous navigation: pipe diameters correctly estimated, junctions detected by robot vision	Untethered configuration, miniature test network	More accurate estimation of the distance to junctions
Traversal speed ≈ 3 m/min in hardware; 5.2 and 6.0 m/min in simulation on two of three routes	Dry network; simulation	Hardware tuning towards the 4 m/min target
Wireless charging and data exchange under water	Wet tests (DMC)	Larger action radius through energy storage and efficiency
UT module integrated in mechanics, power and CAN communication; all interfaces worked as designed	DMC test set-up, M36	Centring of the UT module in the pipe
Inspection images, localisation data and robot logs transferred through base stations to the Central Data Storage	Interface tests (T4.3, T8.1)	—
20 m tether removing charging times and enabling in-pipe debugging and data logging	Wet and dry tests	—



Figure 2: Snake-like robot: (a) UT module integrated into a shortened robot configuration, (b) 20 m tether system with spool and connector

Navigation was verified in the miniature test network of Figure 3, which combines a warped DN110 PE pipe, large- and tight-radius 90° bends, gate valves, DN110 and DN160 T-sections and a DN160→DN110 diameter transition.

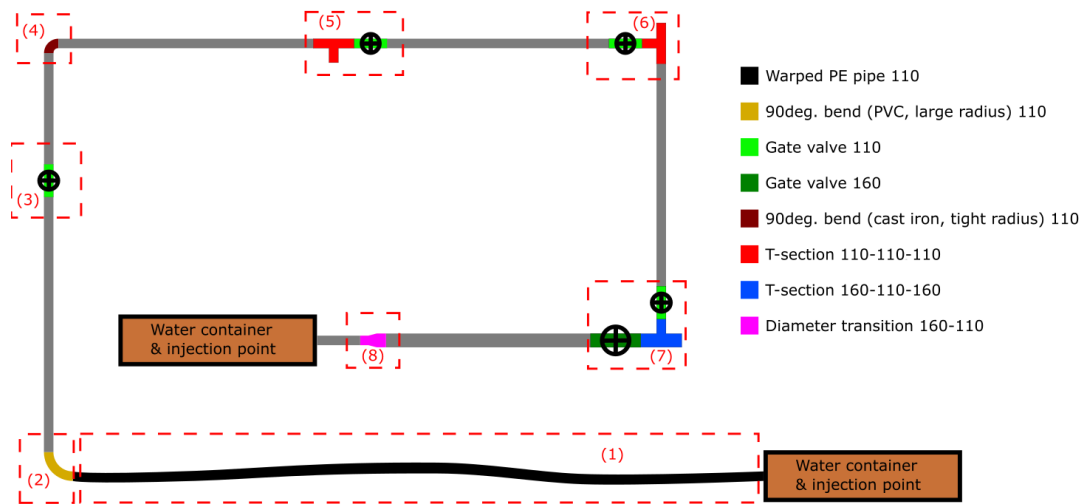


Figure 3: Miniature test network used to verify the autonomous navigation of the snake-like robot

Extensive wet testing identified watertightness as the limiting factor for repeated field trials: leaks recurred after testing and repairs, and connector water damage caused internal communication faults. A new connector concept was designed and verified, but integrating it would have required a major redesign of the robot. Together with the EC Project Officer and the reviewers, the consortium therefore redirected effort to the soft robots and re-hosted the UT module on the inspection soft robot (§2.3). The software, simulation environment, interfaces and design know-how of the snake-like robot are retained as an exploitable asset for life tests once the hardware is made pressure-tight.

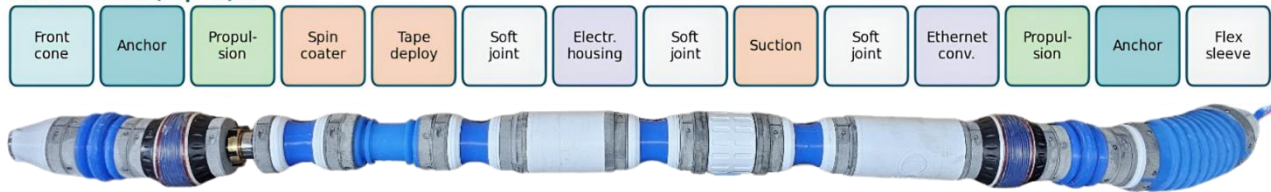
2.2 Soft Robots

All soft robots are assembled from one **modular, tethered, pneumatically actuated platform** (BBL; patent application filed). Interchangeable modules connect in series through a universal IP68 connector, so the same library configures into a maintenance robot, an ultrasonic inspection robot or a lightweight visual-inspection robot (Figure 4). Three design choices carry most of the performance:

- **Hollow-core / eccentric modules** let pneumatic lines, power and data pass along the robot axis, which is what allows tooling to be stacked in series.
- **Overlapping gait control**: the six-state peristaltic cycle runs as 11 time-overlapping steps, shortening the cycle period; a rigid two-point anchor fixture keeps slip near zero.
- **Off-board actuation and Ethernet telemetry**: a 12-DOF pneumatic platform outside the pipe drives the robot through the tether; on-board USB→Ethernet conversion is designed for up to 150 m.

TUBERS – D8.2 Report on TUBERS Performance Assessment

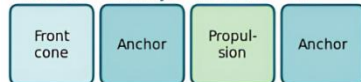
Maintenance (repair) robot



Inspection (UT) robot



Lite visual-inspection robot



← front end



■ Anchoring ■ Propulsion / steering ■ Tooling / payload ■ Electronics / telemetry ■ Passive compliance

Figure 4: Module configurations of the three soft robots that were developed during the TUBERS Project.

Table 5 summarises what the soft robots can and cannot yet do, with the evidence for each statement.

Table 5: Soft-robot capability matrix

Can (demonstrated)	Evidence	Cannot yet	Reason / next step
Traverse 45° and 90° elbows, T- and Y-junctions, ball valve, DN110↔DN150 step, forward and reverse	Bendabl, Jul 2026, both robots – D8.3	Operate inside a pressurised live main	Anchor sealing and dewatering against working pressure not yet qualified
Climb a vertical pipe carrying tether and tooling	Vitens Nov 2025; Bendabl Jul 2026 – D8.3	Navigate autonomously	Operator-driven; gait parameters tuned manually per robot
Travel at 1.2 m/min	Mock-up Tests, Vitens Preliminary Demonstration, Bendabl Final Demonstration D5.3/D8.3	Travel beyond the tether length	20 m tether used; 150 m telemetry qualified by design only
Pass pipes down to ≈10 cm diameter	Mock-up Tests, Vitens Preliminary Demonstration, Bendabl Final Demonstration D5.3/D8.3	Cover beyond the 30 cm upper range	Scaled module set (DN160–DN250) designed and validated in lab, not integrated to a TRL 6 setting.
Isolate a chamber, dewater, clean, dry and deploy repair in-situ; stop a leak in real time	Mock-up Tests, Bendabl final demonstrator, 2.5 mm hole in PE/PVC, 2 repairs, up to 64 mm cracks with a 1.4 mm width – D5.2/ D5.3/ D8.2/ D8.3	Repair axial cracks up to 200 mm	Crack specimens tested radially. Durability under pressure and drinking-water certification of the tape pending
Provide in-situ visual feedback with selective omnidirectional movement of the camera	Vitens Nov 2025; Bendabl Jul 2026 – D8.3	Provide 4K resolution underwater	Sensor resolution provides 1080p full HD footage, more advanced sensors require investigation.
Run a synchronised 360° ultrasonic scan over ~15 cm	Bendabl, water-filled – D8.2/D8.3	Provide repeatable and explainable data due to misalignment issues	Soft robot inherent compliance introduces misalignment. Alignment mechanism for repeatable inspection required.

2.2.1 Inspection Specifications

The inspection robot carries the ultrasonic (UT) housing between its two propulsion modules, so the probe can be translated across a defect while both anchors stay locked. Operators enter the pipe internal diameter, sound velocity in the pipe material, sensitivity threshold, nominal wall thickness and expected pulse width; the robot then alternates 360° scans and ~5 mm axial steps, plotting a thickness map in real time (Table 6).

Table 6: Inspection robot specifications

Parameter	Value
Configuration	Front cone – anchor – propulsion – UT housing – soft joint – Ethernet converter – propulsion – anchor – flex sleeve
Length / mass / max. outer diameter (deflated)	≈ length=1200mm / weight=3.2kg / OD=90mm
Pneumatic DOF	10 drivers: 2 anchors, 2 × 4 propulsion chambers
Operating Pressure	0.5-2 bar for soft actuators
Power Average	24V=0.5A (12W)
Pipe diameter demonstrated	DN110–DN150 (Bendabl)
Sensing	Front camera + LED ring; UT probe with actuated mirror (360°), IP68 housing with own IMU and electronics
UT scan	~5 mm axial zone per 360° scan; ~15 cm observable area between anchors; real-time C-scan and profile
Telemetry / tether	USB→Ethernet converter on board; 20 m tether; UT link over serial (115 200 baud)
Speed	1.2 m/min in automated locomotion cycle

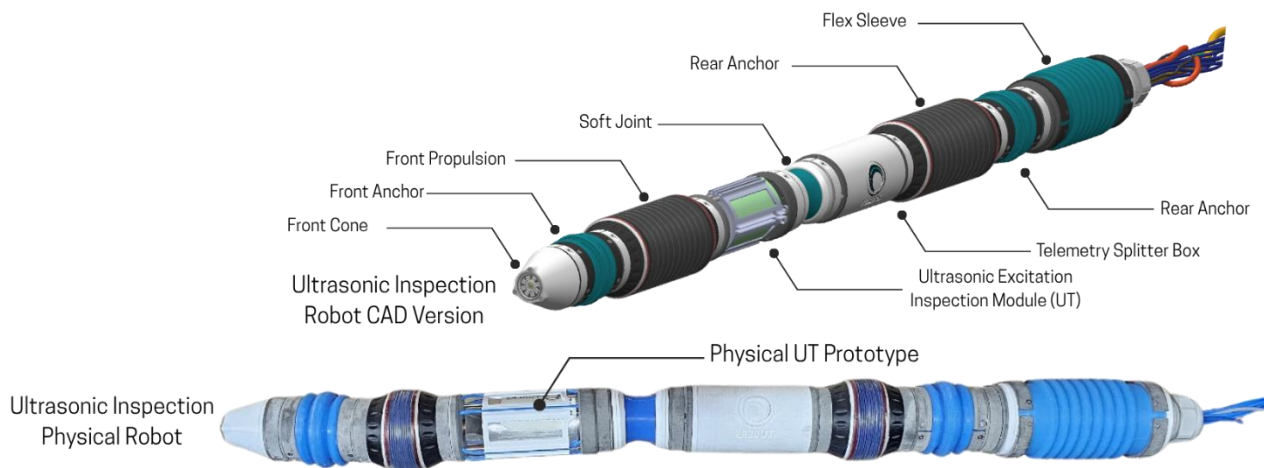


Figure 5: Inspection Soft Robot

2.2.2 Maintenance Specifications

The maintenance robot is the maximum-capability configuration: it isolates a chamber with its two anchors, evacuates water with a gravity-aligned suction module (off-board double-diaphragm pump), cleans and dries through the eccentric spin-coater nozzle, and seals the defect with the slotted tape-deployment actuator. Antagonistic control of the two propulsion modules moves the tooling across the defect while the anchors stay sealed (Table 7).

Table 7: Maintenance robot specifications.

Parameter	Value
Configuration	Front cone – anchor – propulsion – spin coater – tape deployment – soft joint – electronics housing – soft joint – suction – soft joint – Ethernet converter – propulsion – anchor – flex sleeve
Length / mass / max. outer diameter (deflated)	≈ length=1700mm / weight=3.8kg / OD=90mm

Parameter	Value
Pneumatic DOF	11 drivers: 2 anchors, tape actuator, 2 × 4 propulsion chambers
Operating Pressure	0.5-2 bar for soft actuators / 6 bar for maintenance
Power	5V=0.9A (4.8W)
Sensing	Navigation camera and mid-body 45° facing camera with LED rings; IMU; pipe pressure and temperature
Repair methods	Underwater adhesive tape (demonstrated); 3-medium spraying via spin coater (polyurea-urethane resin, water, air)
Surface preparation	De-watering: off-board diaphragm pump connected to rotating gravitational suction module. Cleaning: booster pump up to ~3 bar with air pulses; drying: air ≥ 8 bar (optional, tape works underwater)
Repair envelope targeted (D3.1)	Holes ≤ 5 mm; axial cracks ≤ 200 mm
Repair envelope demonstrated	2.5 mm hole in PE/PVC, underwater, then pressurised; 64 mm radial cracks in PE/PVC
Repair cycle time	Approx. 4 min for sealing (i.e. first application of tape and supplementary pressurisations to ensure adhesion)

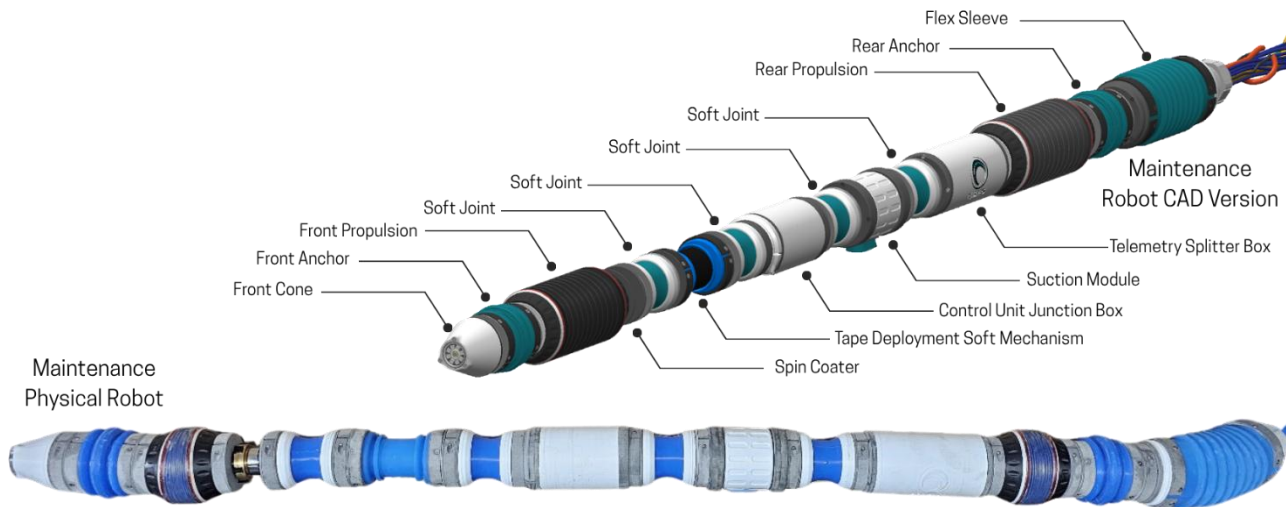


Figure 6: Maintenance Soft Robot.

2.2.3 Lite Specifications

The Lite robot is the minimal locomotion core with a front camera. It was assembled as a lite version of the robot (interim review, Dec 2025): a fast, agile carrier for pure soft-locomotion benchmarking and for visual data collection with UESS, independent of the heavier tooling (Table 8).

Table 8: Lite visual-inspection robot specifications.

Parameter	Value
Configuration	Front cone – anchor – propulsion – anchor
Length / mass / max. outer diameter (deflated)	≈ length=450mm / weight=1.2kg / OD=90mm
Pneumatic DOF	6 drivers: 2 anchors, 1 × 4 propulsion chambers
Operating Pressure	0.5-2 bar for soft actuators
Power	5V=0.4A (2W)
Best speed	1.2 m/min
Demonstrated	Complex features incl. T-junction; vertical climb; in-pipe images of cracks and holes for WP7
Sensing	Front camera

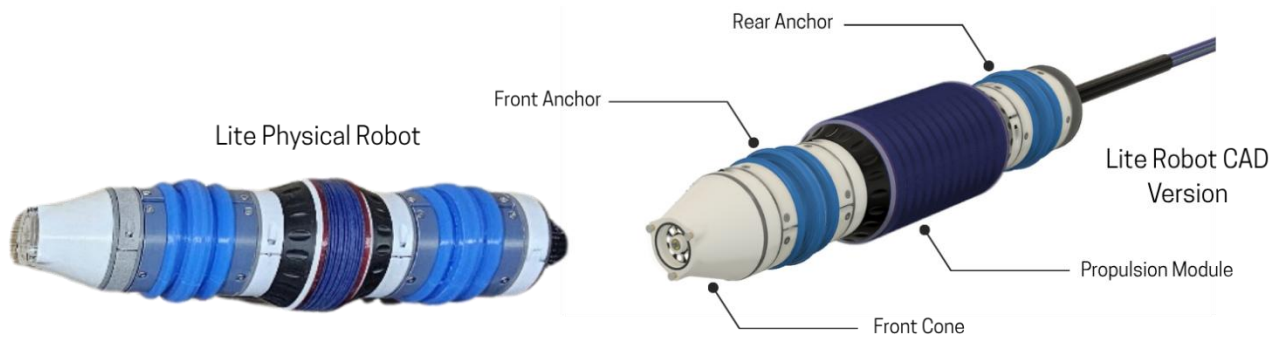


Figure 7: Lite visual-inspection soft robot.

2.3 Ultrasonic

The UT module (WP6, THL) provides non-destructive, 360° wall-thickness inspection from inside the pipe. A single 5 MHz immersion probe fires onto a motorised rotating mirror, so one channel covers the full circumference. Custom electronics on four stacked boards (high-voltage pulser, receiver front-end, FPGA/ARM system-on-chip and motor driver) process the signals on board and transmit only the results to the host robot. Table 9 lists the specifications and the performance verified in the laboratory (D6.2).

Table 9: UT module specifications and verified performance

Parameter	Value	Evidence
Housing	Stainless steel, Ø55 × 107 mm, IP68, potable-water compatible	D6.2
Probe and scanning	5 MHz immersion probe with rotating mirror; 360° circumferential scan	D6.2
Pulser	Up to 200 Vp-p; five levels (±100 V, ±50 V, 0 V); coded excitation supported	D6.2, bench
Receiver	0.5–9 MHz (–3 dB); 0–48 dB gain; 16-bit, 125 MS/s; SNR ≈46 dB	D6.2, bench
Compliance with EN ISO 22232-1	Gain-linearity error 0.42 dB (≤1.6 dB allowed); digitisation error ±2 % (±5 % allowed)	D6.2, bench
Wall-thickness accuracy / rate	Better than 0.2 mm; up to 2 000 scans/s	D6.2, metallic and plastic samples
Minimum defect detected (K3.1)	< 0.5 cm²; 1.5 mm calibration hole resolved	Laboratory
Minimum leakage detected (K3.2)	2.5 L/min at 3 bar	RP1 bench campaign
Power	6–48 V DC, 4.8 W	D6.2
Host interfaces	CAN (snake-like robot); CAN-to-TX/RX bridge to the ESP32 (soft robot); shared GUI with C-scan and CSV/PNG export	RP3

Laboratory tests covered steel calibration blocks, a 12 mm stainless-steel plate with artificial pitting and PVC pipe sections with drilled holes and wall-loss patches. Figure 8 shows circumferential B-scans of an immersed grey PVC pipe: the inner and outer wall echoes clearly bound the ≈6 mm wall, and the artificial defects appear as interruptions of the back-wall echo with intermediate indications. The defects remain detectable at 92 rpm as well as at 6 rpm, i.e. at about 15 times the rotation speed, which is what makes fast in-pipe screening feasible.

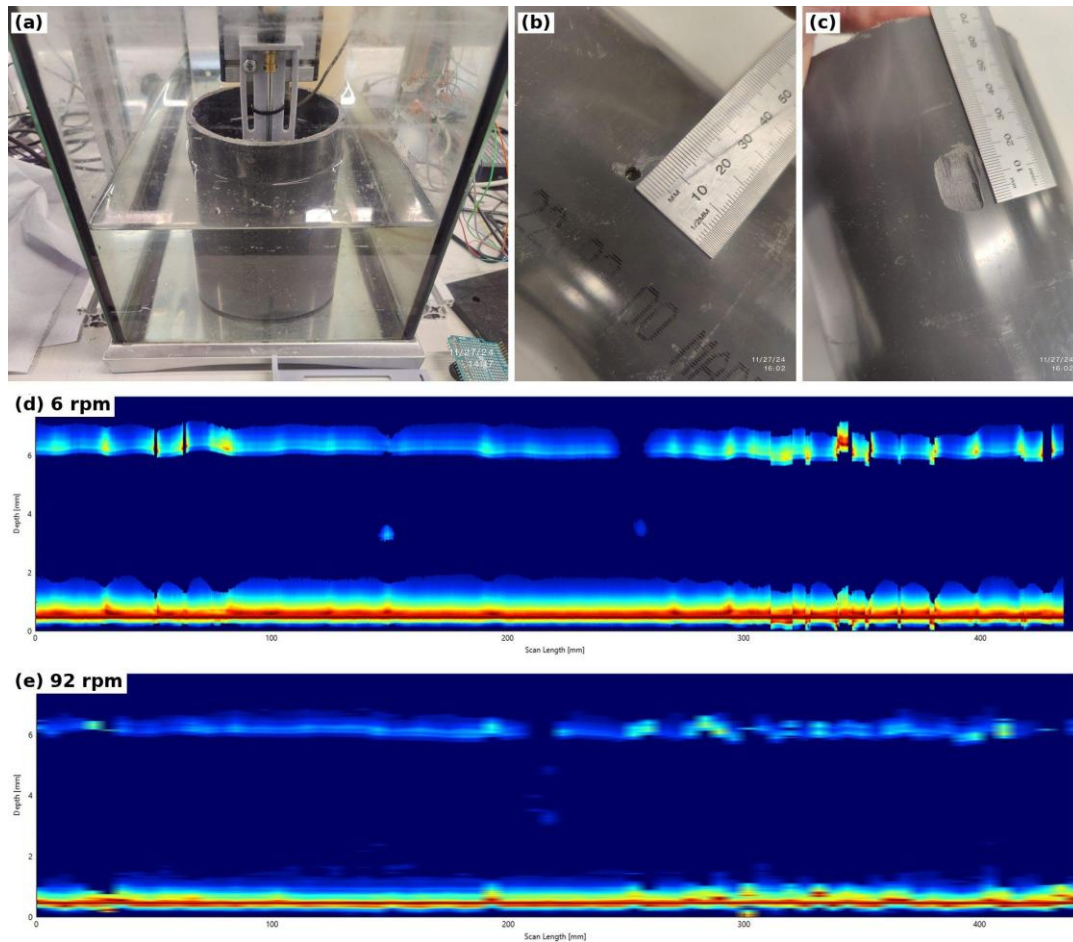


Figure 8: Laboratory B-scans of a grey PVC pipe with artificial defects: (a) immersion set-up, (b) drilled hole, (c) wall-loss patch, (d) B-scan at 6 rpm, (e) B-scan at 92 rpm

The module was first integrated into the snake-like robot (M36), where mechanics, power and CAN communication worked as designed (§2.1). After the module stopped transmitting data during the Netherlands campaign, a bottom-up troubleshooting procedure isolated the fault to the CAN transceiver of the FPGA board; all other subsystems (pulser, receiver, motion assembly) were confirmed operational and the board was replaced. Following the decision to re-host the module on the inspection soft robot, THL and BBL adapted it on three fronts (Figure 9): a housing with guiding channels that carry the pneumatic lines past the module, a custom PCB that bridges the unchanged UT firmware to the robot's ESP32 controller, and UT blocks in the common Inspection GUI for scan configuration, acquisition, live C-scan display and data export to BBL and UESS.

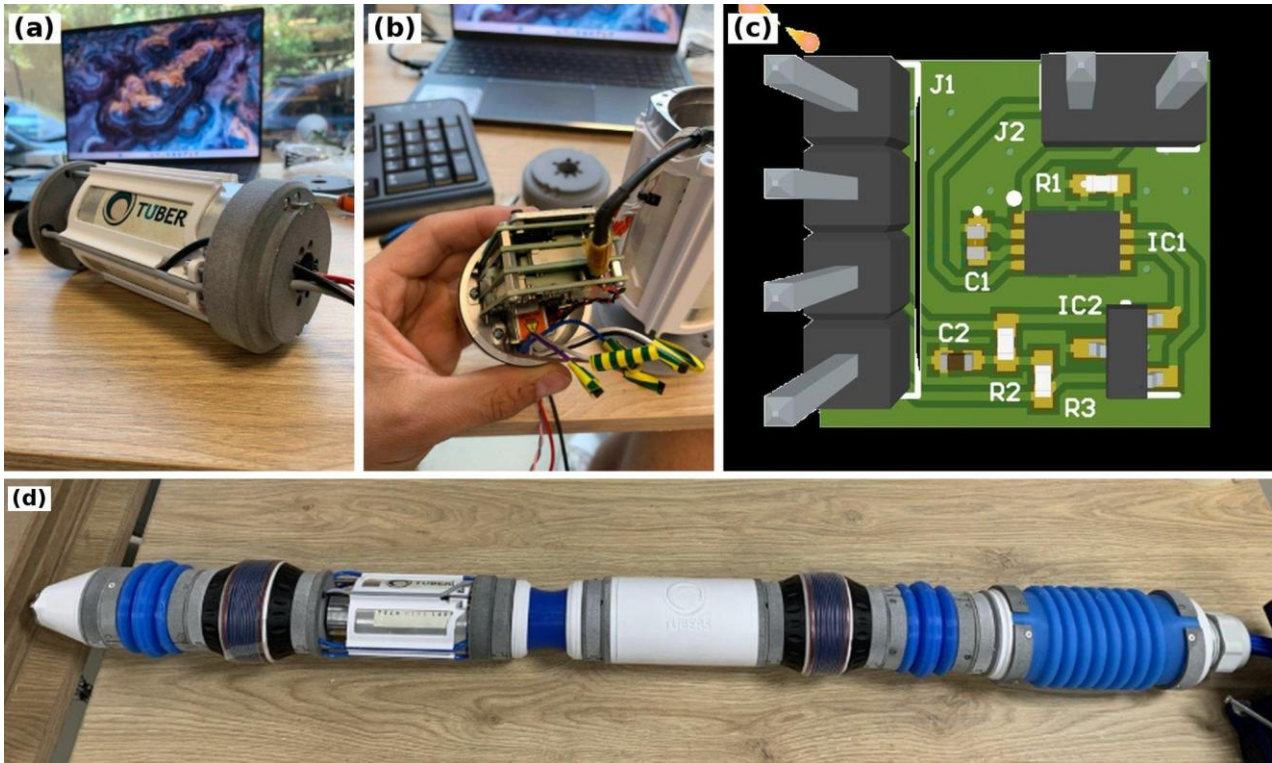


Figure 9: UT module adapted to the inspection soft robot: (a) housing with guiding channels for the pneumatic lines, (b) electronics stack, (c) CAN-to-TX/RX interface PCB, (d) inspection soft robot with the integrated UT module

At the final demonstration the complete chain (i.e. soft-robot locomotion in 5 mm axial steps, 360° acquisition, transmission, live C-scan and export) ran in-pipe for the first time (§3.2.3). The compliant robot body did not hold the probe coaxial with the pipe, so the thickness readings in that configuration were not consistent. THL reproduced the condition in the laboratory with a soft jig (Figure 10): with the best alignment the C-scan returns a consistent wall thickness of 4.2–4.4 mm over most of the circumference, apart from the expected dead zones behind the pneumatic lines, whereas a misalignment of only 2–5° scatters the readings. This confirms that the UT electronics and firmware perform as designed and that probe alignment is the single condition for valid in-pipe data. Three refinements follow:

- **Alignment:** a rigid centraliser or spring-loaded guides around the module to hold the probe coaxial with the pipe.
- **Dead zones:** double-pass scanning with a slight rotation of the robot, merged in post-processing.
- **Motor coasting:** position-based mirror control, replacing the current manual row-shift correction in the GUI.

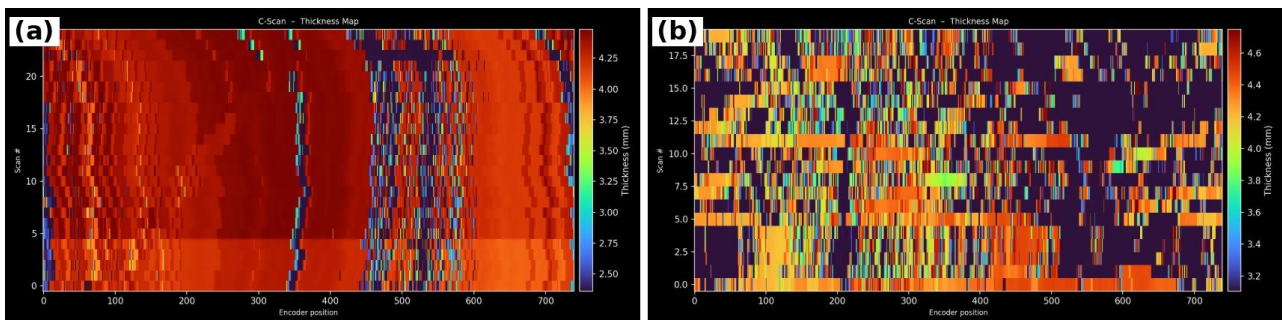


Figure 10: Laboratory C-scan thickness maps with the UT module held in a soft jig: (a) best achievable alignment, (b) misalignment of approximately 2–5°

2.4 Decision Support System & Machine Learning Models

The explainable machine learning models exploited in the Decision Support System were trained to perform binary crack classification on visual data collected from the project's soft inspection robot, assisting the operator in deciding whether a Point of Interest (POI) constitutes a defect. The target performance for this task, as set out in the Grant Agreement, is under 10% false positives and under 10% false negatives. Two real-condition demonstrations were used to assess the models and the DSS beyond the lab test set. The first one consists of the Vitens demonstration (November 2025), which served as preliminary real-data collection and an early system-level test, and the second was the Athens demonstration (July 2026), the final integrated demonstration, in which the model trained on the Vitens dataset was expected to generalise to a different but similar test network.

Publicly available real-world pipe defect datasets were also considered as a potential additional training source. These were found to come from a substantially different environment to the project's use case. Most defects in these datasets were introduced from outside the pipe rather than inspected from within, the available inside-pipe imagery was predominantly of concrete rather than plastic pipe, and several datasets did not include negative (no-defect) samples at all. As a result, no useful training could be carried out on these datasets, and models trained on them were not evaluated in either demonstration.

They were used only for a separate generalisation test of the project's own pretrained model, which showed that classification recall is sensitive to image viewpoint, with down-the-pipe views achieving substantially higher recall than close-up views. This is an important consideration when interpreting the demonstration results below.

2.4.1 Vitens demonstration (November 2025)

During the first full-scale soft robot test at the Vitens facilities, 5 defects were introduced into the test network, ranging in size from 1.3 cm to 11.5 cm. Model development progressed from an ImageNet-pretrained VGG16 baseline (0.72 test accuracy) to a full improved configuration incorporating data augmentation, a deeper classifier head, learning rate scheduling and partial fine-tuning, reaching 0.95 accuracy on the held-out test set (46 true positives, 52 true negatives, 4 false positives, 1 false negative). Evaluation was carried out at the image level rather than per discrete defect, since the number of defects that could physically be introduced in this setting was limited. The report accordingly records the count of correctly classified images against this dataset rather than a per-defect detection rate.

The full improved classification model achieved a false-positive rate of 7.1% (4 of 56 defect-free images) and a false-negative rate of 2.1% (1 of 47 defect images) on the held-out lab test set, comfortably within the Grant Agreement KPI target of under 10% for each metric. The Vitens and Athens demonstrations further validated this performance under representative field conditions, successfully closing the loop from inspection through classification and decision support.

The Decision Support System itself was not evaluated during this demonstration, since the models available at that point had been trained only on synthetic data. DSS evaluation was consequently deferred until after the demonstration, once the model trained on the real Vitens dataset was available.

2.4.2 Athens demonstration (July 2026)

During the final integrated demonstration, 2 defects (2.5 mm holes) were introduced, one in a transparent acrylic pipe section and one in a PE/PVC pipe section. Only the PE/PVC pipe defect was used for model evaluation, under both dry and water-filled conditions.

The defect introduced in the transparent pipe was not evaluated by the model, since the training data did not include comparable transparent-pipe imagery, and the classifier's applicability to this pipe material has therefore not yet been established. The same model trained on the November 2025 Vitens dataset was used for this evaluation, with no retraining between the two demonstrations. Example outputs of the classification model are demonstrated in Figure 11.

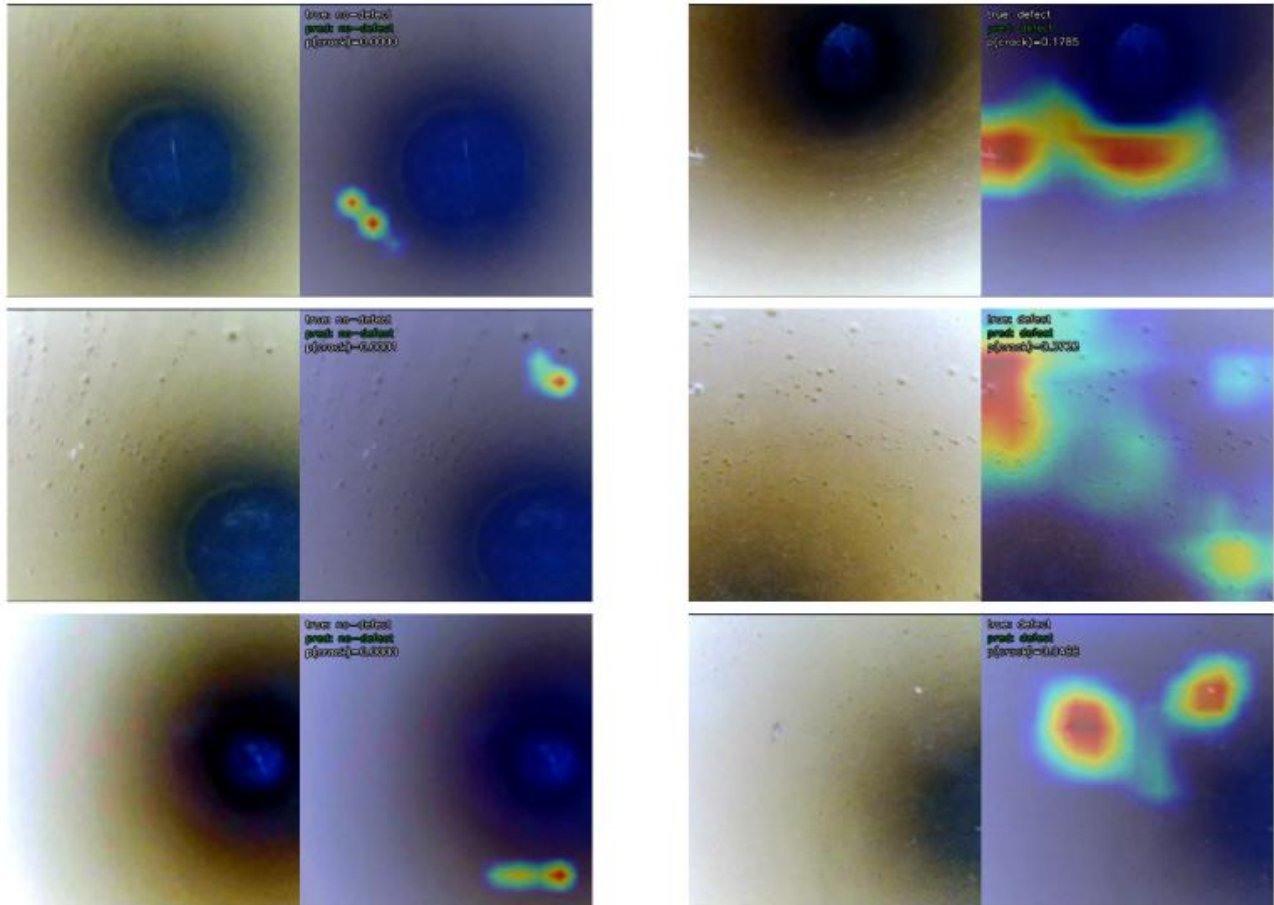


Figure 11: Example outputs of the classification model on the PE/PVC pipe during the Athens demonstration. Each pair shows the endoscopic frame (left) and the corresponding Grad-CAM overlay (right), annotated with the ground-truth label, the predicted label and the crack probability. Left column: defect-free sections. Right column: frames containing the introduced defect.

The target for the Decision Support System was real-time synchronisation between the robots, the central data storage and the operator interface. This target is met in practice. The upload from the robot is effectively instantaneous, limited only by the available internet connection, and the machine learning models process the uploaded images as a batch in approximately 42 seconds. All other interactions with the central data storage, including the defect/no-defect annotation choice, repair task submission, and task status updates surfaced from the Bendabl repair UI, propagate to the operator interface on the order of milliseconds, so that the user perceives these updates as instantaneous.

The programmed pipe replacement date shown in the Repair Analytics panel is currently based on a placeholder value. Next steps could involve an additional operator-facing section where the specifications of a given network, such as material, installation date and existing maintenance schedule, are entered once per network. The Programmed Pipe Replacement, Cost Analysis and Environmental Impact estimates will then be computed directly against the actual network being inspected, further strengthening the credibility of the DSS's maintenance-planning output.

2.4.3 Future Work

Building on the results presented above, two further steps could consolidate this evidence base and enhance the Decision Support System. Continued field deployment would expand the evidence base of real, physically introduced defects across a wider range of sizes and wet/dry conditions in the PVC and PE pipe materials used in water networks, building further statistical confidence around the KPI position already established on the lab test set. This ongoing field data collection is also the natural route to characterising performance across viewpoint and inspection distance under real operating conditions. In parallel, the Decision Support System should be extended with the network-specification input described above, so that its maintenance-planning estimates can be computed directly against real network data for an operational deployment.

3. System Evaluation

3.1 1st Demo at Vitens Facilities (Nov 2025)

The Vitens round was the first stage of T8.2 and, in the terms of this report, the **preliminary validation**: it de-risked locomotion on industrial components at a water utility's own premises and allowed the final campaign to concentrate on repair (interim review, 1 December 2025). It took place in November 2025 and was combined with Workshop 1 (23 attendees).

3.1.1 Set-up

All equipment was shipped on one Euro-pallet: the V5.0 robot (3–5 kg, 15 × 15 × 180 cm case), two pneumatic platforms (pressure and vacuum), booster, diaphragm and resin pumps, the tether and spares. The test network combined valves, a Y- and a T-junction, PVC and transparent pipes, 90° bends, 45° tight bends and a vertical pipe, with an entry point, the pneumatic control platform and a control laptop (Figure 12). In addition, DMC shipped a specialised endoscopic device to inspect the performance of the robots from inside the pipe network and gather feedback on the locomotion performance of both robots.

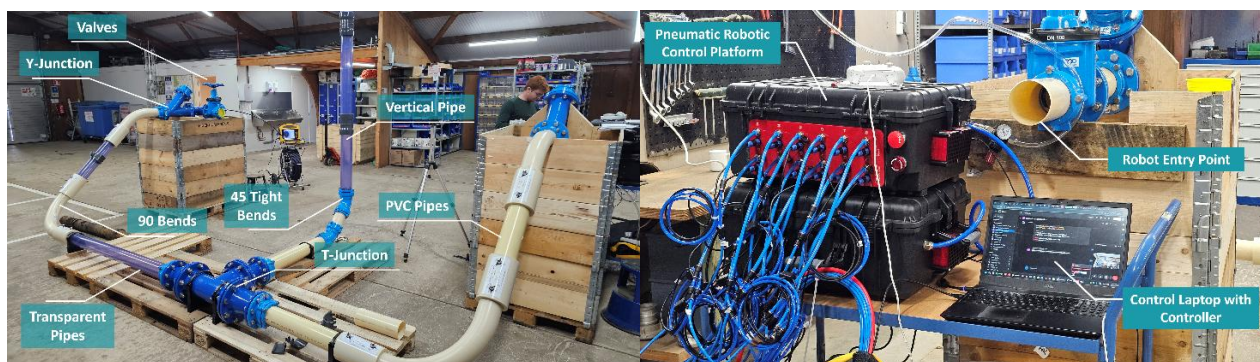


Figure 12: Test network and control station at the VITENS facility, November 2025.

3.1.2 Tests and results

Table 10: Tests run at VITENS.

#	Robot / condition	Objective	Outcome
1	Full (V5.0) – dry	Traverse complex industrial terrain; climb vertical pipes	Demonstrated; 1.2 m/min with manual tuning
2	Lite – dry	Traverse complex industrial terrain	Demonstrated incl. T-junction; 1.2 m/min with manual tuning
3	Full (V5.0) – wet	Watertightness; reach leak site; perform maintenance cycle	Maintenance cycle performed; ingress protection in all components but camera enclosures
4	Lite – wet	Watertightness; collect visual leakage data; climb vertical pipes	Crack and hole images collected with UESS for WP7 training; no water ingress

The best traversal speed of the project, **1.2 m/min (20 mm/s)**, was obtained here by both robots in dry pipe under manual tuning, 20% above the 1 m/min (16 mm/s) KPI and above the threshold that was defined by the industrial partners in the consortium. Number of runs and distance: **8 total runs** (2 runs for each experiment) with a **cumulative distance of 120 m** travelled by both robots.

During the trials both versions of the robot were assessed for their ability to traverse the network, navigate complex features, maintain watertightness, climb inclined and vertical pipes, capture defect

footage, and perform a maintenance cycle (dewater, surface preparation). Footage from the operation of the full robot is presented in Figure 13.

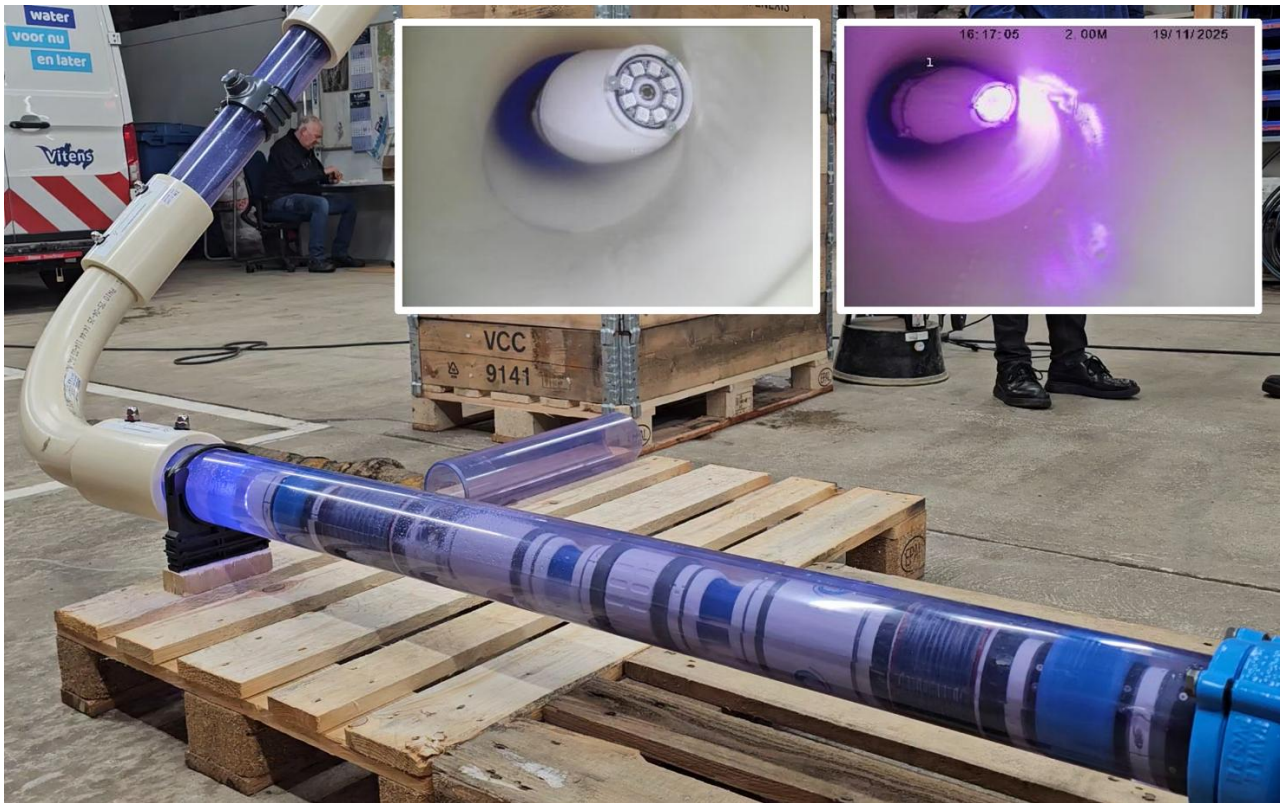


Figure 13: VITENS Preliminary Trials - Full Robot Wet Tests.

The average speed of each robot was measured using the time required to reach different sections of the network and the overall distance travelled calculated by the nominal lengths of the components. Evidence of the lite robot navigating a complex tee-junction and climbing a vertical pipe is presented in Figure 14.

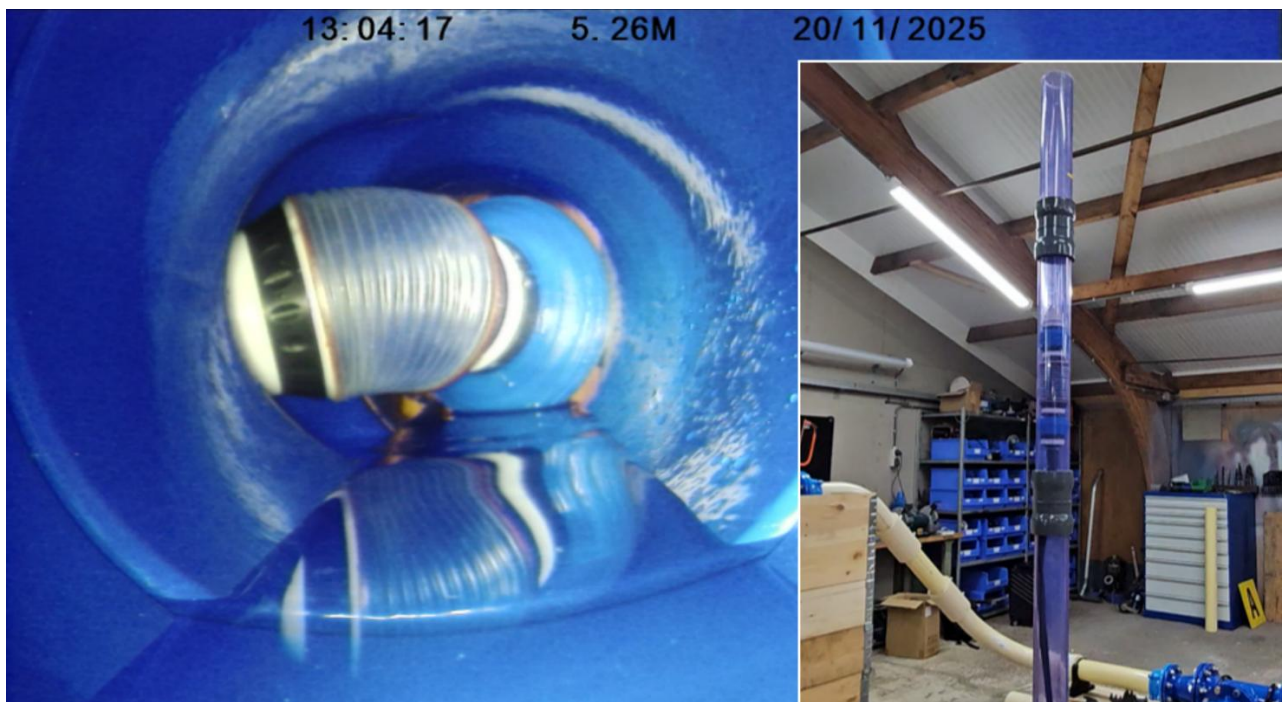


Figure 14: VITENS Preliminary Trials - Lite Robot Operation Evidence.

Finally, a joint operation activity between Bendabl and the University of Essex demonstrated the capability of the robot to be used in a real application of performing in-situ data collection from defective pipes to capture visual information regarding punctured holes and cracks from inside a pipe. Evidence is presented in Figure 15.

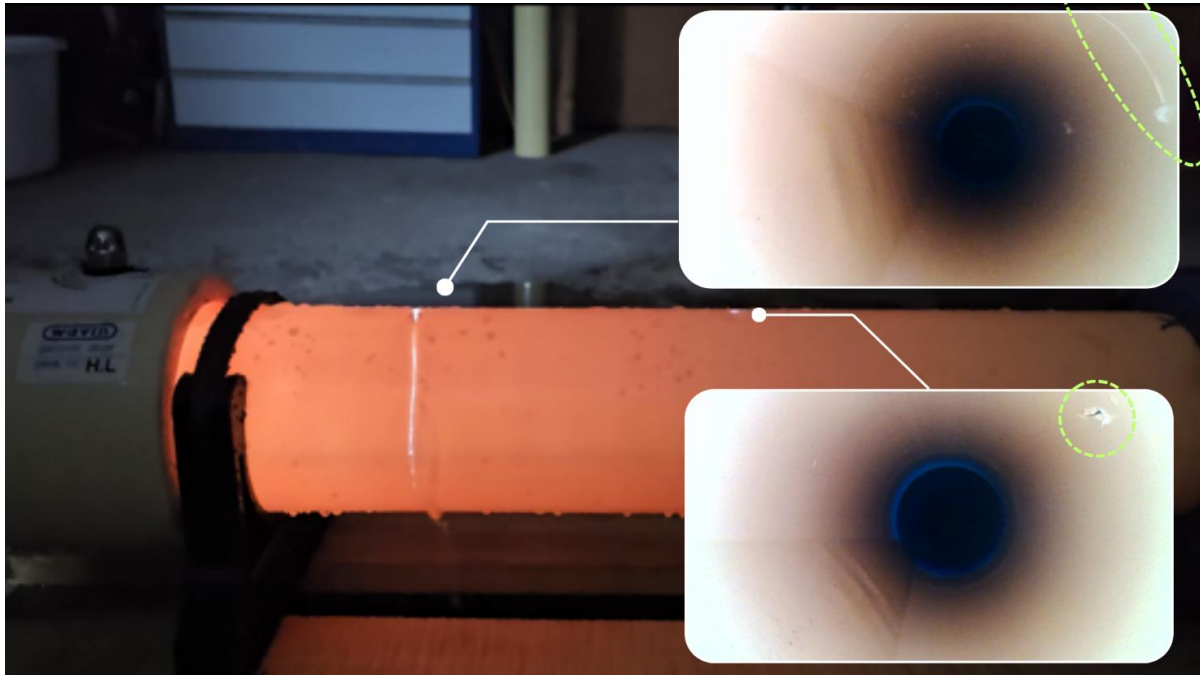


Figure 15: VITENS Preliminary Trials - In-Situ Data Collection (BBL/UESS)

With no snake-like carrier available at VITENS, the in-pipe deployment of the UT module was validated with the utility's own inspection equipment: VITENS provided a push-rod system that its crews use routinely for pipe inspection. A custom two-part adapter was designed for the purpose, with one half clamping onto the push-rod head by a tight interference fit and the other onto the UT housing, the two joined by four threaded rods (Figure 16). With this assembly the UT module was inserted into the DN110 test pipe, confirming its mechanical interfaces, its dimensional compatibility with the target pipe size and the feasibility of deploying it with standard industry tooling. This also gives the UT module a fallback deployment route that does not depend on a robotic carrier.



Figure 16: VITENS Preliminary Trials - UT module mounted on the VITENS push-rod system with a custom adapter

A fault on the UT electronics board occurred before the measurement runs started, so no ultrasonic data were recorded at VITENS. The UT electronics stack was subsequently troubleshoot component by component (February–March 2026) and brought back to an operational state, enabling the synchronised in-pipe scans demonstrated at Bendabl (§3.2).

3.1.3 Fidelity gaps

Table 11: Differences between the VITENS tests and the target environment.

Simplification	Effect on validity	Justification
System end-to-end testing	Subsystems tested individually with offline integration.	Stage focused on locomotion; robot insertion and maintenance capabilities. Data collected were processed offline and Ultrasonic operation was tested using a custom device.
UT module not on board	No in-pipe UT data	UT integration planned for 2026 and risk mitigation measures were activated after the interim review results (December 2025)
Spin-coater operation only	Tape deployment not assessed	Repair component demonstration deferred to the final campaign
Snake-like robot not tested	Inspection carrier watertightness did not permit field testing.	Integration of UT module to the snake-like robot descoped and mitigation measure for soft robot integration planned for final demonstration.

3.1.4 Issues found and fixes carried into the final robots

The preliminary findings retrospective (December 2025) turned the VITENS demonstration results into five work streams; Table 12 lists each finding and its fix.

Table 12: VITENS findings and the corrective actions implemented before the final campaign.

Finding at Vitens	Fix in the final robots
LED-ring sealing failed (front cone, junction box)	Watertight front cone with enlarged O-ring seat; redesigned LED-ring cover; validated O-rings
Mixed 3- and 4-screw patterns left hub, suction and repair modules 30° misaligned	Uniform 4-bolt modular connectors
Thin connector walls; threaded inserts came loose	Wall-thickness optimisation; alternatives to inserts; corrected manufacturing tolerances
LED-ring cables tangled and at risk of being cut	3-core cable with CAN-bus twisted pair; slot milled in the spin coater stator
Pump residue jammed the nozzle; torque multipliers unscrewed or snapped	Single-ring torque multiplier; cleaning steps in the operation manual
Flex sleeve deformed permanently	Harder silicone; improved connector grip
Surface-preparation risk for resin repair (R5.2)	Underwater adhesive tape and soft deployment mechanism added as primary repair method
Long-tether signal transfer (Raspberry Pi over Ethernet)	ESP32 architecture over USB with on-board USB→Ethernet converter with capacity of telemetry up to 150 m (Cat6 Ethernet protocol)
Housing material degradation over time	Low-cost prototype materials (PLA) substituted with engineering materials (combination of ABS and PA12)

3.2 2nd Demo at Bendabl Facilities (Jul 2026)

The final demonstration was held at the **Bendabl test facility** in Athens, Greece on **13–17 July 2026**, on a TRL 6 test bed built from real industrial components supplied by the consortium's water utilities. Representatives of the Dutch water utility companies and of the Greek utility company EYDAP attended; Workshop 2 gathered 20 attendees over three days. The goals were to (i) validate the complete workflow (i.e. inspection, ML classification, DSS decision, robotic repair and task

closure); (ii) collect the evidence for D8.3 and the current report, and (iii) capture end-user feedback. Table 13 compares the planned and executed schedule.

Table 13: Planned versus executed schedule

Day	Planned	Executed
1	Assemble DN110–DN150 network, configure control, tune robots, early baseline tests	Preparation of the final demonstration carried out the week before the final demonstration.
2	First runs of the three sequences; preliminary data (benchmark photos, UT scans)	Each sequence was executed independently prior to the final workshop.
3	Uninterrupted end-to-end rehearsals; evidence collection	End-to-end rehearsals took place 1 day before the final workshop.
4	Live demonstration workshop with end users	Presentation of findings (BBL, UESS, THL); live end-to-end demonstration; feedback session
5	Repaired segments post-op leakage testing	Brabant Water conducted dedicated leakage tests according to industrial protocols to assess the quality of the repair process.
6	Retrospective and report planning	Retrospective and assessment of the findings took place in the consortium general assembly that took place on July 17 th .

3.2.1 Demonstration Site and Experimental Setup

The final demonstration was held at Bendabl's facilities, on a network built from industrial components provided by the water companies, to limit troubleshooting and the delays introduced by shipping the robotic components. The network (Figure 17) led from an inclined PE/PVC pipe through a 45° elbow into a metal T-junction stepping DN110→DN150, where the robots climbed a branch featuring 45° and 90° elbows, into the elevated straight PE/PVC pipe carrying the artificial leak; an extended route continued through a transparent section, a Y-junction with a ball valve connected in series and a 90° elbow into a vertical transparent pipe.

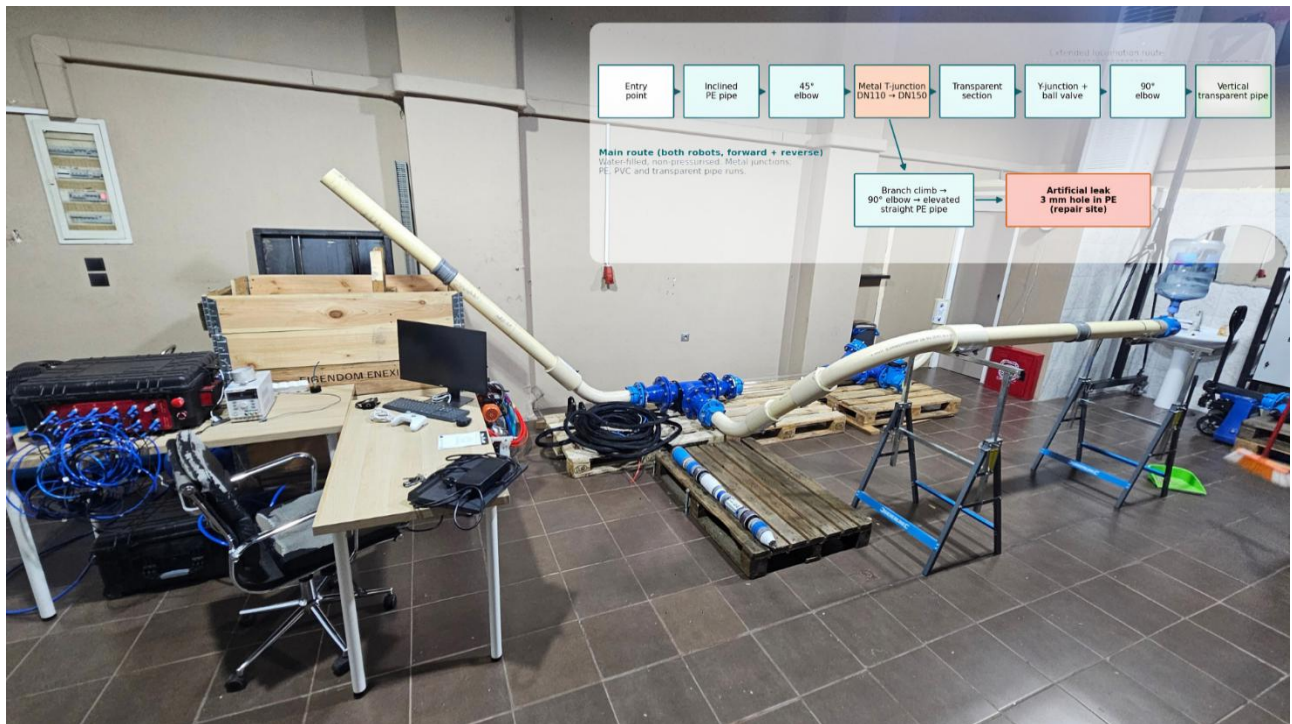


Figure 17: The Bendabl TRL6 Testbed - July 2026

3.2.2 Test design and data recording

Four subsystems developed during the TUBERS project were evaluated: the inspection robot (§2.2.1), the maintenance robot (§2.2.2), the Ultrasonic Testing Module (§2.3) and the DSS with the Central Data Storage (§2.4). The mission ran as three operator roles (Figure 18): inspection, post-inspection decision and repair, followed by validation of the task status. The acceptance criteria were fixed before the campaign in the Demonstration Plan M46 and are listed with the results in Table 14. Evidence was recorded through the operator GUIs (valve pressures, IMU, pipe pressure/temperature), the on-board and endoscopic cameras, the UT C-scan and profile and Firebase task timestamps, all consolidated in the D8.3 demonstrator deliverable video.

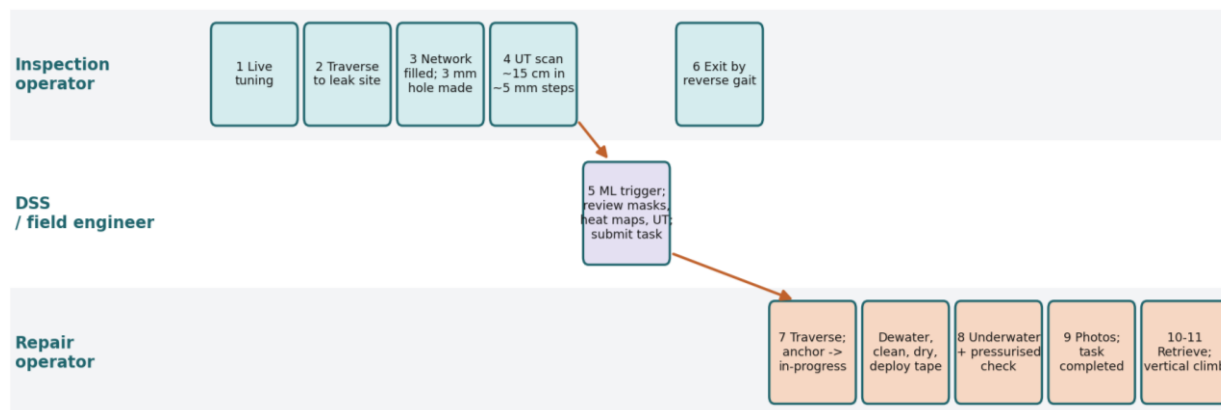


Figure 18: Mission sequence and role assignment for the final demonstration, run end to end

Through a structured, step-by-step sequence distributed across three discrete operator actions (i.e. Inspection, Decision Support System, Repair), the demonstration validated the complete end-to-end operational workflow. This encompasses the initial physical inspection, automated Machine Learning (ML) defect classification, seamless data synchronisation and task generation via the Decision Support System (DSS), and the robot-assisted repair process. The week-long session was strategically phased to prioritise rigorous technical calibration and baseline data gathering, culminating in a comprehensive live demonstration workshop for end-users and key stakeholders. The overview of the demonstration protocol that was designed to capture the complete functionalities of the TUBERS system is presented in Figure 19.

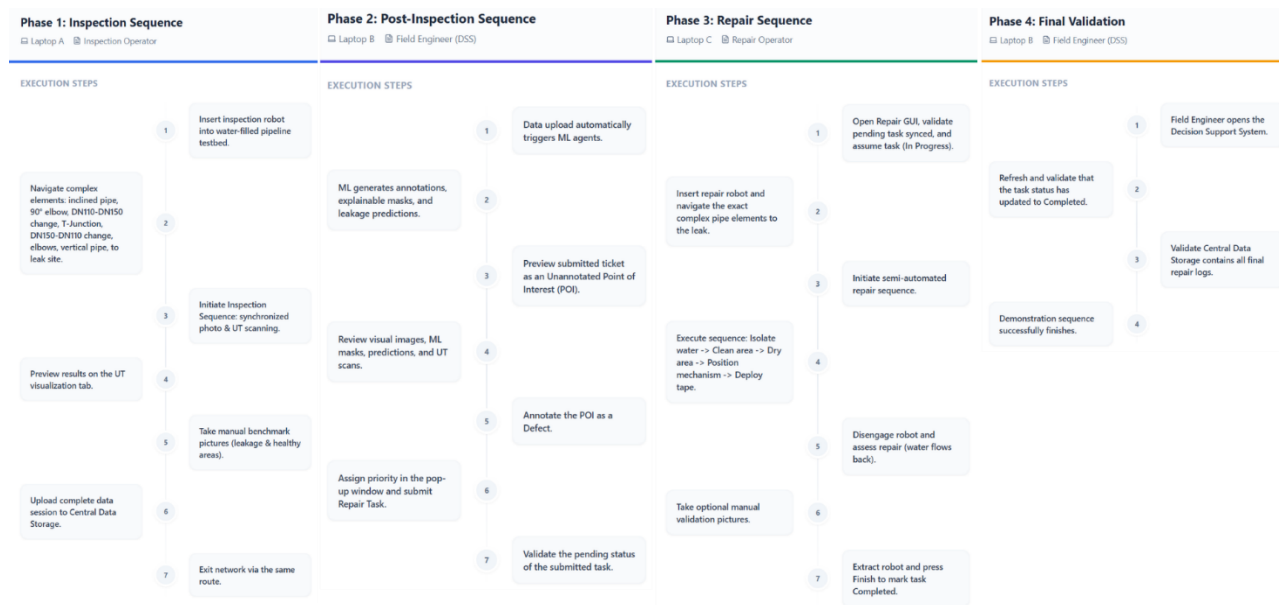


Figure 19: Final Demonstration Plan - Bendabl, July 2026

3.2.3 Results and discussion

The full chain ran end to end with no step simulated: the artificial leak was found, scanned, classified, planned for repair, sealed underwater and closed in the DSS, with the task moving from the inspection operator to the repair operator through one system. **Two leaks** were repaired in total. All nine demonstrable assets of the plan were achieved (Table 14).

Table 14: Acceptance criteria and results

#	Acceptance criterion	Result	Status
A1	Traverse elbows, T-junction, vertical and inclined pipes	Both robots passed 45° and 90° elbows, the T-junction and the branch climb, forward and in reverse; both climbed the vertical pipe	Achieved
A2	Traverse DN110↔DN150	Step passed by both robots; manual control at the T-junction (D5)	Achieved
A3	Watertight operation in water-filled pipe	Both robots operated water-filled; water level checked through the robot camera	Achieved
A4	Identify and repair the leak	Defect in PE/PVC located, scanned, sealed with tape; leak stopped in real time; no leak after re-pressurising	Achieved
A5	Operate both robots	Both completed their sequences and were retrieved by reverse gait	Achieved
A6	Pass the task inspection → DSS → repair	Status moved automatically to in-progress on anchoring and to completed on finish, in local system, database and DSS; repair photos attached	Achieved
A7	Predict the defect on images	ML triggered on upload; segmentation masks and explainability heat maps shown	Achieved
A8	Show decision-support information	Next scheduled replacement, nearest access point, water loss vs crack size, CO ₂ and cost vs replacement, priority	Achieved
A9	Map wall thickness around the defect	Thickness map over ~15 cm in ~5 mm steps plotted live. Explainability of the captured data requires precise alignment.	Partially Achieved
M1	Traversal speed ≥ 1 m/min (K2.4)	Average speed recorded stands at 1.2 m/min for the designed locomotion sequence.	Achieved
M2	Repair time ≤ 6 min/leak (K2.2)	Average tape deployment time considering additional inflation actions to ensure adhesion stands at less than 6 minutes on average	Achieved

Both robots reached the leak site along the full main route. The metal T-junction stepping DN110→DN150, the most demanding feature of the network, was traversed by the inspection and the maintenance robot alike, forward on the way in and in reverse on the way out (Figure 20). At this feature the operator switched to manual control, actuating individual chambers to steer the front module into the branch, while the endoscopic camera inserted from the opposite side streamed every passage to the attendees.

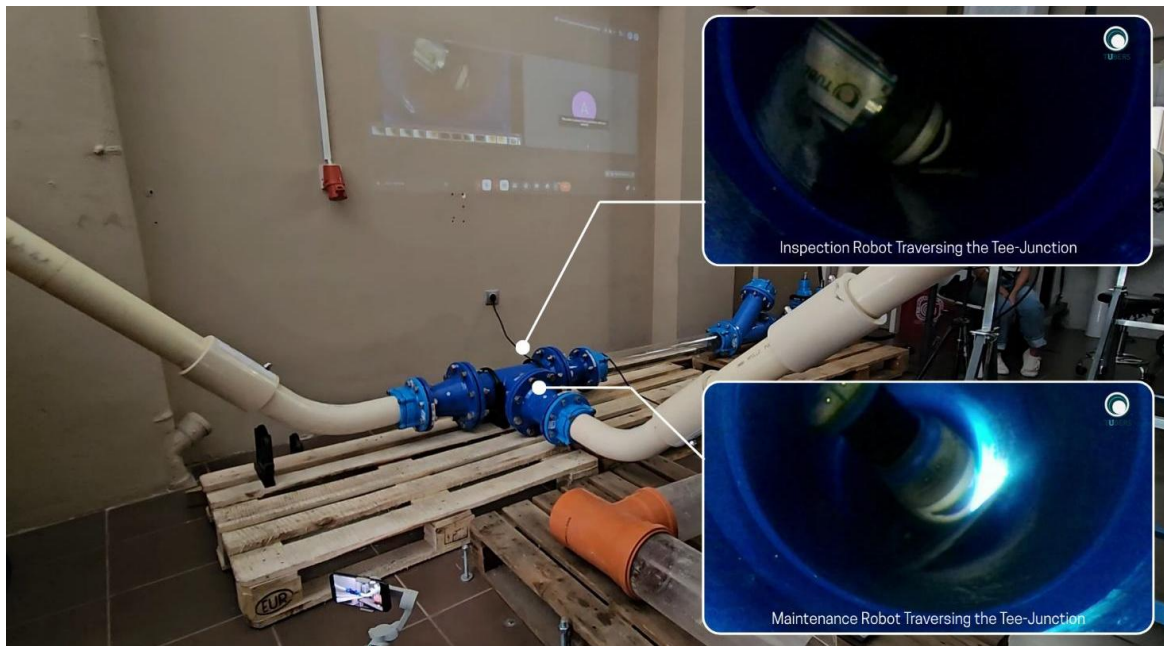


Figure 20: Inspection Robot and Maintenance Robot navigating the Tee-Junction to reach the leakage site.

Both carriers operated fully immersed in the water-filled network with no ingress into their electronics housings (Figure 21), confirming the sealing redesign carried over from the Vitens retrospective (§3.1.4). Water levels were verified through the robots' own cameras before the leak was introduced.



Figure 21: Inspection Robot and Maintenance robot operating under wet conditions, fully immersed in water.

Two artificial leaks were introduced in front of the attendees (Figure 22): a hole in the elevated industrial PE/PVC pipe, used for the complete end-to-end mission, and a hole in a transparent acrylic section, used to show the repair mechanism at work from outside the pipe.



Figure 22: Two defects were demonstrated in the workshop. PE/PVC Pipe (Left) for demonstrating the end-to-end process and Transparent Acrylic Pipe (Right) for demonstration purposes.

At the leak site the inspection robot anchored with the defect between its distal ends and ran the synchronised ultrasonic sequence from the Inspection GUI (Figure 23). After the operator entered the pipe parameters (internal diameter 103 mm, sound velocity 2380 m/s, nominal wall thickness 3.5 mm, threshold 0.1, pulse width 2.75 mm), each 360° scan was plotted live as a C-scan thickness map and scan profile, next to the navigation camera, the IMU pose, the defect location and the valve pressures. Reliable interpretation of the thickness map depends on the coaxial alignment of the probe (A9), which is the main point to refine for this subsystem.

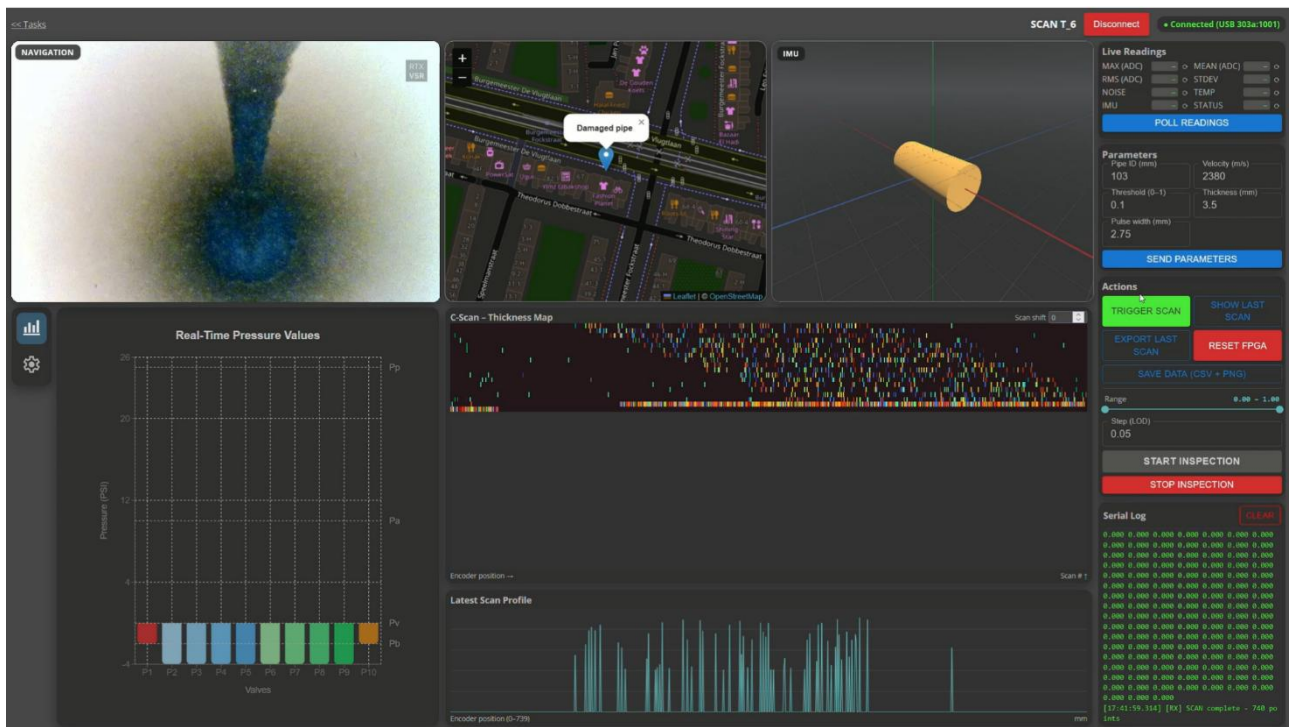


Figure 23: Integration of the Ultrasonic Module to the Soft Robot and synchronised operation.

Completing the inspection sequence uploaded the session to the Central Data Storage and triggered the ML models automatically. In the Inspection Panel (Figure 24, left) the field engineer reviewed the raw images, segmentation mask, explainability heat map and ultrasonic scan, and confirmed the defect. The Repair Analytics panel (right) has been designed to show the next scheduled pipe replacement, the defect location and nearest access point, information on water loss versus crack size, and the cost, lifespan gain and CO₂ emissions of robotic repair against segment replacement. The final step of the inspection process was to set the priority based on the information available in the DSS and submit the repair task.

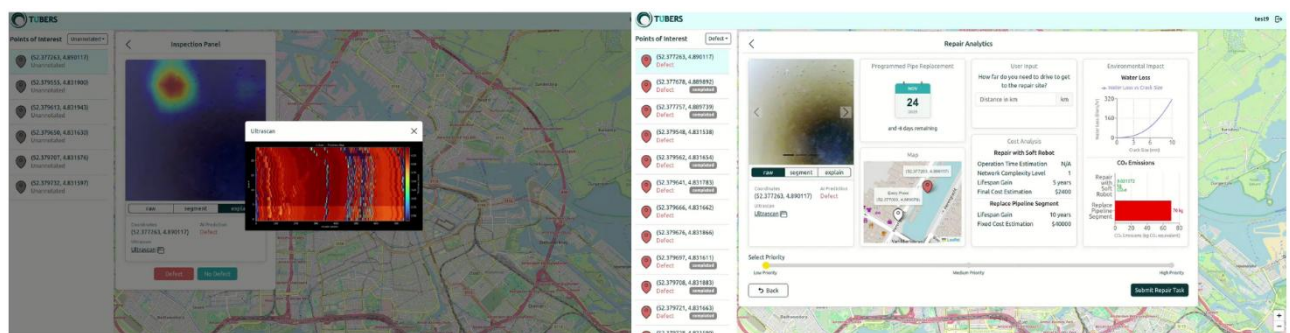


Figure 24: System integration by validating post-processing through the DSS.

The repair operator selected the task in the Repair GUI and drove the maintenance robot along the same route. Anchoring across the defect isolated a chamber and moved the task to in-progress; the chamber was then dewatered, cleaned and dried, and the tape was deployed (Figure 25). On inflation the slotted actuator unfolds (A–B), the slots reach a critical displacement and tilt outward (C), and the tape is released and pressed onto the pipe wall (D); the insets show the corresponding FEA of the slot mechanism. A final inflation of the front anchor applied homogeneous pressure to secure adhesion. Including these additional inflations, tape deployment took less than 6 minutes on average (M2).

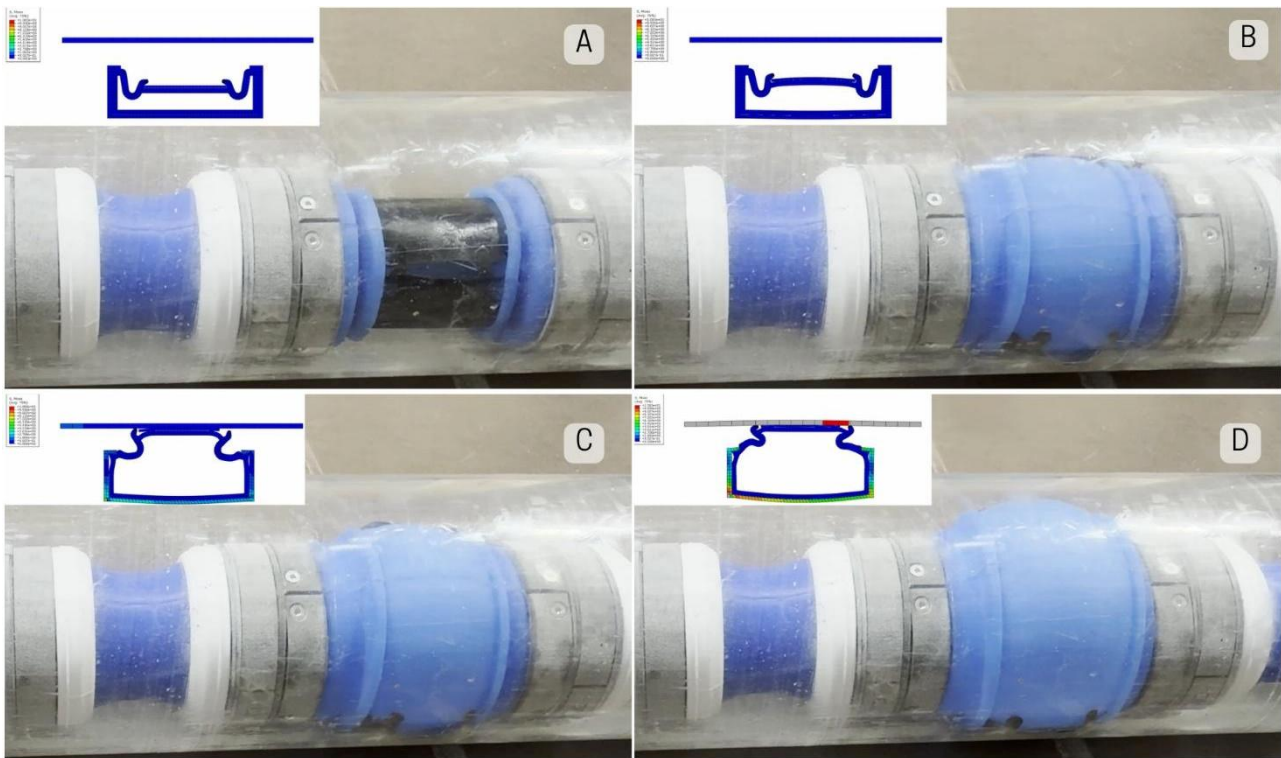


Figure 25: Repair Sequence step-by-step process.

To show underwater adhesion and real-time leak stoppage, water was reintroduced and the isolated chamber was pressurised through the spin-coater nozzle during deployment; the leak stopped as the tape adhered. The chamber was then pressurised again and the repair was inspected from outside with no leakage observed. Throughout the sequence the Repair GUI (Figure 26) gave the operator both camera views, the valve pressures, the IMU pose and the pipe pressure and temperature.

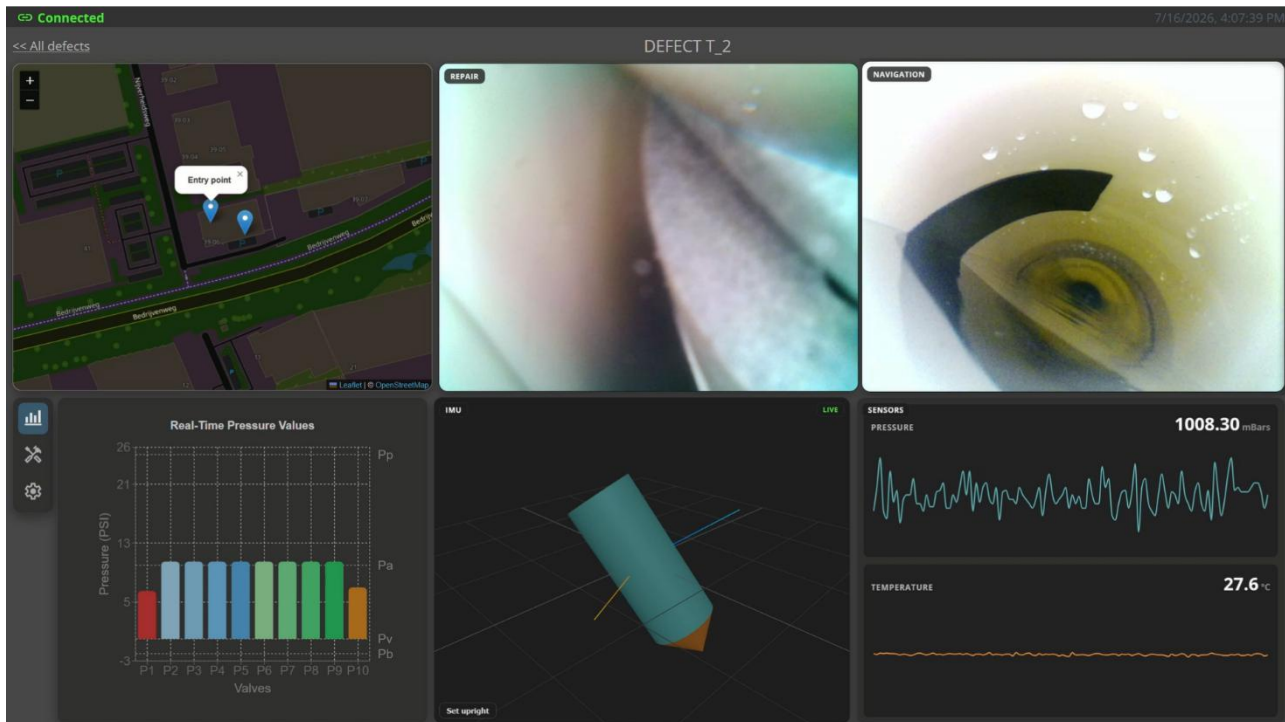


Figure 26: Validation of successful repair operation.

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The operator reversed the robot to photograph the deployed tape, uploaded the images as task metadata and closed the task. Its status changed to “completed” simultaneously in the local system, the database and the DSS, where the repair photos remain attached to the point of interest (Figure 27). The robot was then retrieved through the T-junction by reverse locomotion.

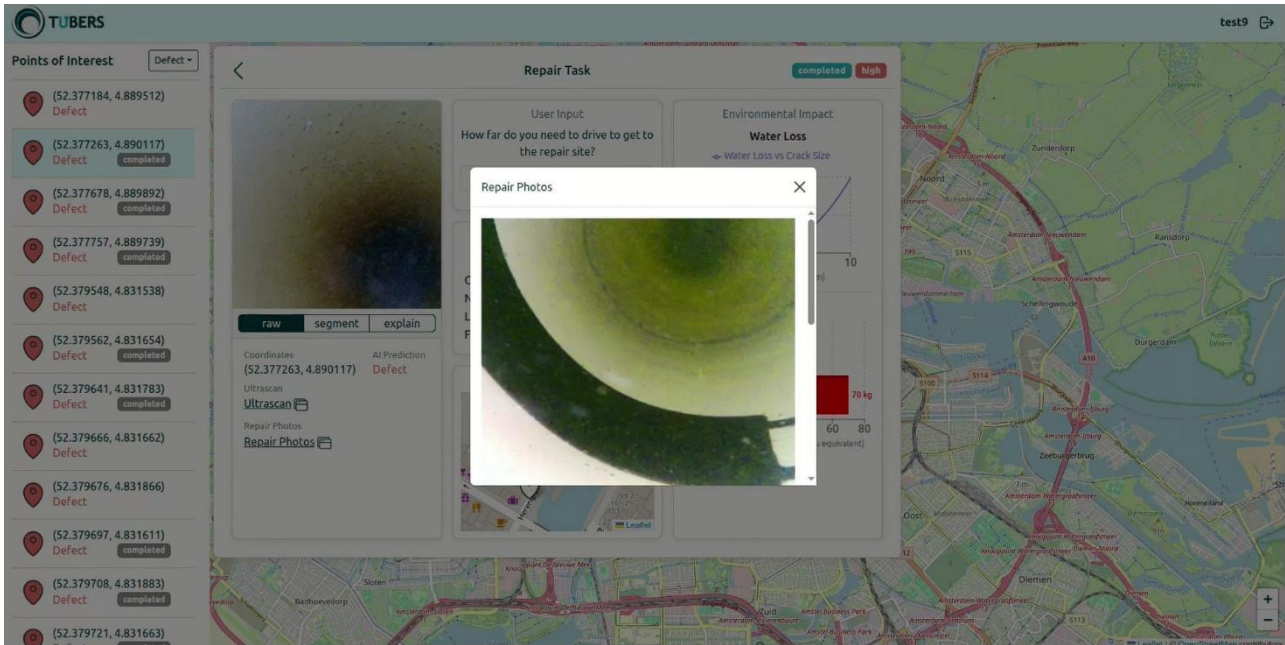


Figure 27: Validating task closure and system integration in the DSS.

After the end-to-end mission, both robots took the alternative route through the transparent section, the Y-junction with ball valve and the 90° elbow, and climbed the vertical pipe (Figure 28). Climbing while carrying the tether and tooling opens applications in fire safety and cooling networks that are otherwise inspected and repaired using extensive scaffolding and removing insulation to reach the pipe; a process that is costly, unsafe and requires extensive human labour.

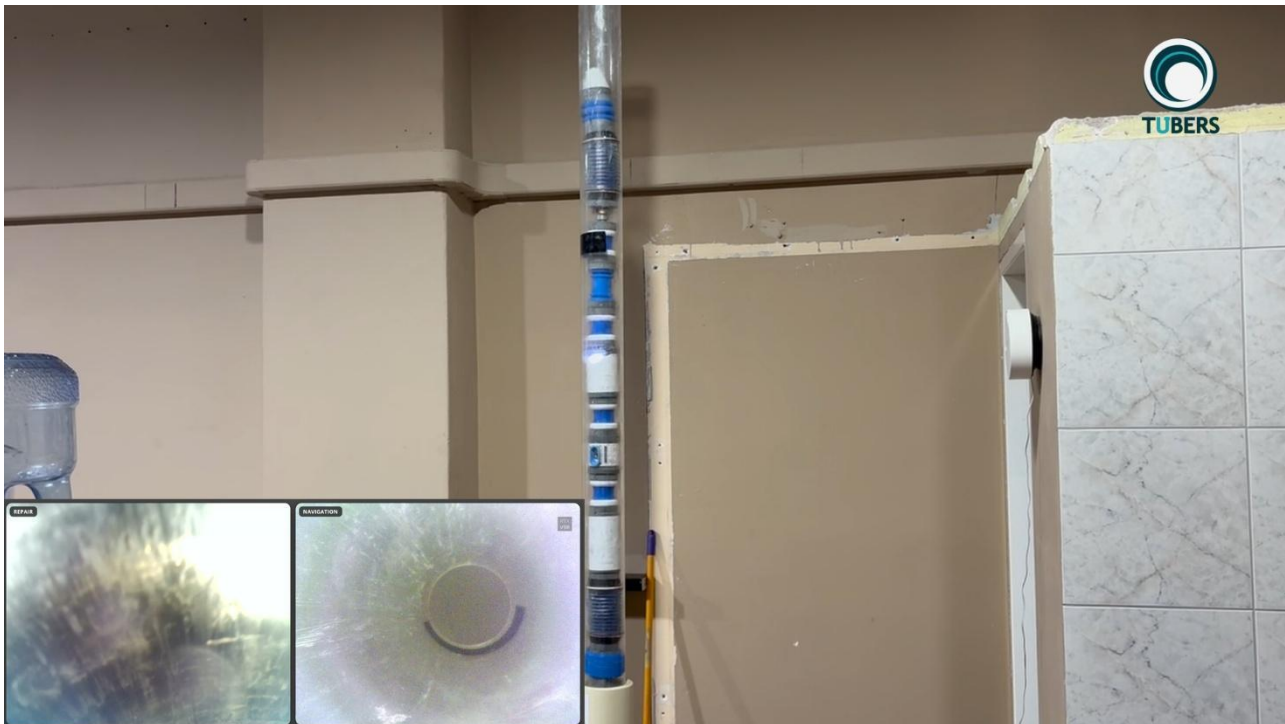


Figure 28: Vertical climbing capabilities demonstration.

Operational observations: No step of the mission had to be simulated or bypassed. The robots were teleoperated with gait parameters tuned live on site (D1, D5); the T-junction was the only feature that required manual control, and S-shaped manoeuvres remained available to free or re-orient the robot.

3.2.4 Post-repair leakage testing

To assess repair quality against industrial practice, four DN110 PE/PVC specimens were repaired with the TUBERS repair tooling and sent to Brabant Water (Figure 29): a ≈ 2.5 mm round hole and a radial crack (≈ 64 mm long, up to 1.5 mm wide), each repaired once with the adhesive tape and once with resin spray. The hole–tape specimen is the one repaired during the final demonstration on 16 July 2026.



Figure 29: Repaired pipe specimens sent to Brabant Water for Leakage Testing.

Brabant Water filled each specimen with water and pressurised it from 1 bar up to 10 bar; a repair that reaches 10 bar and holds it for at least 5 minutes is rated successful. **Both tape repairs passed**, holding 10 bar on the hole and on the 64 mm crack. This confirms the underwater tape as the primary repair method and evidences a sealed defect more than three times the 2 cm length targeted in the GA (K2.3). The resin spray repairs started leaking at 5 bar (hole) and 3 bar (crack); improving the material selection process, mixing and in-pipe curing of the resin is retained as a development item for the secondary repair method.

3.2.5 Comparison against Grant Agreement targets

Table 15 compares every KPI of Table 3 with the best measured result and its conditions, using four status values: Met, Partly met, Not assessed and Re-scoped. Figure 30 shows the KPIs with a single quantified result normalised to their targets.

Table 15: KPI traceability: target versus achieved

ID	Target	Best result (where, when, conditions)	Status	Gap-closing action
K1.1	WP4 - Speed 4 m/min	≈3 m/min hardware, dry network; 0.8 / 5.2 / 6.0 m/min in simulation on three routes	Partly met	Watertightness-first hardware redesign and further tuning to reach the simulated speed of 6 m/min.
K1.2	WP4 – Localisation Accuracy 98 %	Reliable autonomous wet operation and 98% localisation in a representative drinking-water network were not validated.	Not Assessed	Validate in a representative network
K2.1	WP5 – Pipe Width Range 15–30 cm	≈10 cm minimum in both demonstrations; DN110–DN150 at Bendabl/Vitens; 30 cm achievable with increased pressure values and scaled design (validated in simulations and lab testing)	Met	Deliver a scaled version of the robot for higher pipe ranges.
K2.2	WP5 – Repair time 6 min/leak	Tape deployment repair takes in total ≈4 min	Met	Repeat in-pipe under pressure
K2.3	WP5 – Crack length 2 cm	2.5 mm hole sealed underwater (Bendabl); 6.4 cm crack sealed in post demonstration. All specimens assessed successfully by Brabant Water.	Met	Repeat in-pipe under pressure
K2.4	WP5 – Speed 1 m/min	1.2 m/min, both robots, dry/wet, manual tuning (Vitens, Nov 2025)	Met	Measure speed water-filled
K3.1	WP6 – Min Defect Size 0.5 cm ²	< 0.5 cm ² (laboratory)	Met	Repeat in-pipe
K3.2	WP6 – Min Leak Size 5 L/min	2.5 L/min at 3 bar (bench, RP1); in-pipe 360° scan demonstrated at Bendabl	Met	Repeat in-pipe under pressure
K4.1 / K4.2	WP7 – False predictions < 10 % FP / FN	Binary crack classifier accuracy 0.95 on PVC-crack images from full-scale testing; FP/FN split; FP rate of 7.1% (4 of 56 defect-free images) and a FN rate of 2.1% (1 of 47 defect images)	Met	Collect additional data from testing fields
K4.3	WP7 - Risk, LCA, LCCA	Repair analytics with cost, lifespan gain and CO ₂ vs replacement, refined by network complexity; exercised live	Met	Validate with utility asset data
K5.1	WP8 – Length traversed (mock-ups) > 3 km	Cumulative Distance across all campaigns exceeded 250 m. Given the re-scoping of the project to consolidate behind the tethered soft robot this number exceeds expectations.	Re-Scoped	Perform further testing in-pipe under pressure
K5.2	WP8 – Length traversed (live) > 1 km	Network was tested under industrial conditions. No pressurised water was introduced.	Partly met	Pressurised qualification first
K6.1	WP3 – Training workshops 2	2 workshops (Vitens, Bendabl) & 1 live demonstration (A&R Expo)	Met	—
K6.2	WP3 – People trained > 50	43 in the two workshops (23 + 20); > 140 including the A&R Expo demonstration (> 100)	Met	—
K7.1	WP2 – Data repositories 2	Zenodo community with ultrasonic, robotic, defect and synthetic repositories (DS1, DS2, DS3, DS4, DS5, DS6, DS7,8)	Met	—
K7.2	WP2 – Repository Entries > 1000 each	110 for DS1, 982 for DS2, 28909 for DS3, 549 for DS4, 130218 for DS5, 704038 for DS6, and 361 for DS7,8	Met	—

TUBERS – D8.2 Report on TUBERS Performance Assessment

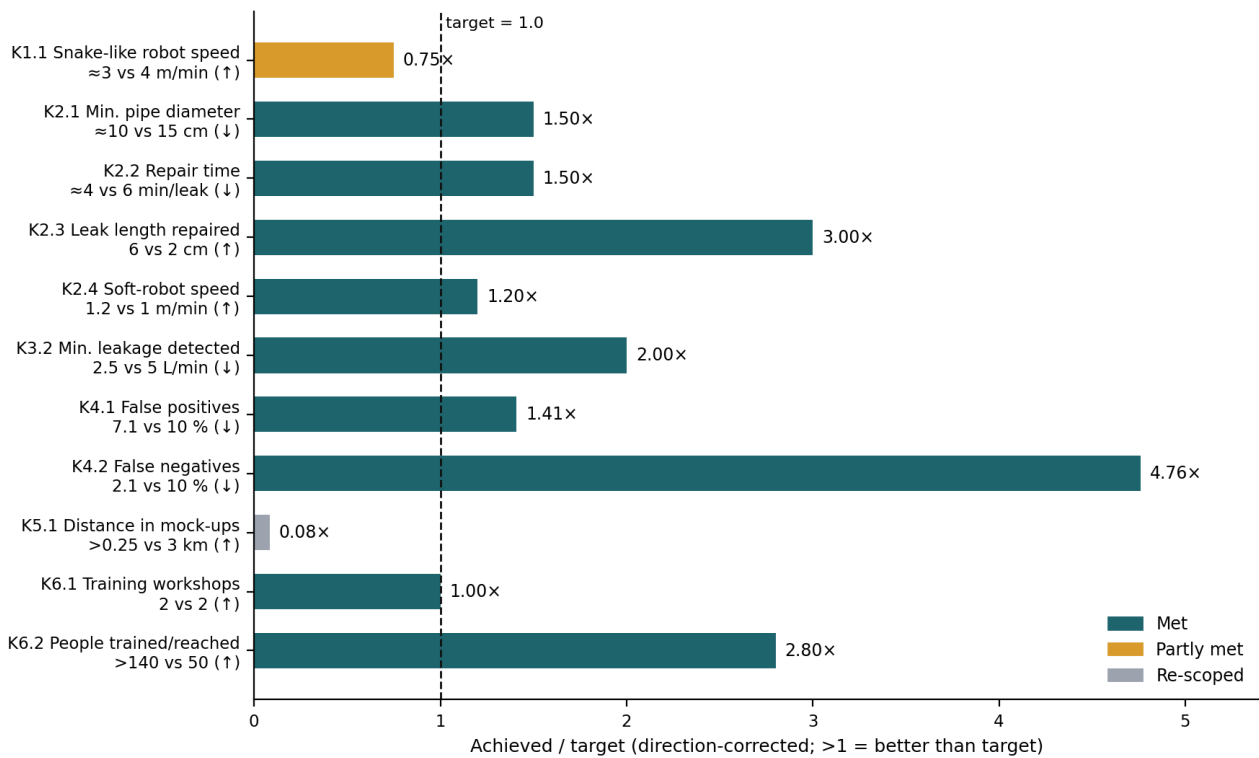


Figure 30: Quantified KPIs normalised to target

Of the 17 KPIs, 13 are met, 2 partly met, 1 not assessed and 1 re-scoped. Several targets are clearly exceeded: false negatives at about a fifth of the threshold (2.1 %), a sealed crack three times the targeted length, leakage sensitivity at half the threshold, repair in ≈4 min against 6 min, traversable diameter below the scoped floor and traversal speed 20 % above target. The partly met KPIs concern the speed of the snake-like robot (K1.1), the absence of a pressurised live-network trial (K5.2); the localisation accuracy of the snake-like robot (K1.2) could not be assessed after its descoping, and the mock-up distance target (K5.1) was re-scoped with the consolidation behind the tethered soft robots.

4. Conclusions

4.1 TRL assessment

The EU definition of **TRL 6** is *technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)*; TRL 5 is *technology validated in relevant environment*. Table 16 argues the level reached per subsystem.

Table 16: Planned versus achieved TRL

Subsystem	Planned	Achieved	Evidence and limits
Soft inspection and repair robots	6	6	End-to-end mission on a water-filled test bed of utility-supplied industrial components (Bendabl) after a first round at a utility's premises (Vitens). Limit: non-pressurised.
Ultrasonic inspection module	6	6	Synchronised in-pipe 360° scan at Bendabl; pressurised sensitivity from bench only.
Explainable ML and DSS	6	6	Automatic trigger, masks, heat maps, repair analytics and task lifecycle run live with robot data.
Snake-like robot	6	5	Dry network and simulation only; wet tests at DMC; wet autonomy not validated.

4.2 Findings

- **End-to-end chain works** → inspection-to-closure mission with no step simulated, two leaks repaired (Bendabl).
- **Topological coverage beyond rigid crawlers** → elbows, T- and Y-junctions, DN110↔DN150, vertical climb, forward and reverse (Bendabl, Vitens), while carrying and operating tooling through a flexible tether.
- **Underwater repair** → robot sealed a 2.5 mm hole with water present and held under re-pressurisation, up to 64 mm cracks were also sealed and held under leakage testing.
- **Speed above KPI** → 1.2 m/min dry/wet with manual tuning (Vitens, Bendabl)
- **UT Sensing under pressure** → 2.5 L/min at 3 bar on the bench
- **ML limited by real data** → 0.95 accuracy on PVC cracks from full-scale tests (FP rate 7.1%, FN rate 2.1%).
- **Range bounded by tether** → 20 m tethers used, 150 m telemetry by design.

4.3 Next steps

Table 17: Prioritised actions towards field deployment

Priority	Action	Proposed owner	Route
1	Pressurised operation: anchor sealing, chamber isolation and dewatering against working pressure	BBL	Follow-up R&D project with utilities
2	Repair qualification: durability, leak-geometry range, drinking-water certification of tape/resin	BBL, ALS, utilities	Certification plan in the exploitation plan (D2.4)
3	In-service training data and FP/FN reporting	UESS, utilities	Data-sharing agreement; Zenodo updates
4	New markets using vertical climbing: fire-water and cooling networks, pipes under insulation	BBL, ALS, THL	Technology transfer discussions started (interim review)

Within the re-scoped project, TUBERS demonstrated at TRL 6 a complete robotic inspection-and-repair chain for drinking-water pipes that no single prior system shows; the distance to field use is characterised and bounded by pressurised operation, repair qualification and certification, and in-service data.