MAELSTROM

MArinE Litter SusTainable RemOval and Management

D3.2

MAELSTROM

Report and videos about the cable robot control with shared autonomy

12/03/2024

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No *[101000832]*

MAELSTROM

General Information

H2020 call	CE-FNR-09-2020 Pilot action for the removal of marine plastics and litter
Grant Agreement #	101000832
Project Title	Smart technology for Marine Litter SusTainable RemOval and Management
Project Acronym	MAELSTROM
Project Duration	January 2021 – December 2024
Project Budget	6 809 461.25 Euros
Related work package	WP3
Related task(s)	T3.3, T3.4, T3.5
Lead Organisation	CNRS-LIRMM
Contributing Organizations	TECNALIA, ST
Dissemination Level	Public

Co-funded by the Horizon 2020 programme of the European Union

MAELSTROM

Authors	Beneficiary
Marc Gouttefarde	CNRS
Cyril Barrelet	CNRS

Authoring & Approval

Approved by	Beneficiary

History of Changes

Version	Date	Author	Description of changes
V0.1	24/04/2023	Marc Gouttefarde	First draft
V0.2	25/04/2023	M. Gouttefarde and C. Barrelet	Second draft
V0.2	26/04/2023	M. Gouttefarde	Final draft
V0.4	05/03/2024	M. Gouttefarde	Revision following external reviewer comment (end of Section 7.5)
V0.5	12/03/2024	M. Gouttefarde	Minor modifications to change from CO to public

Co-funded by the Horizon 2020 programme of the European Union

Executive Summary

The MAELSTROM project aims to test and evaluate innovative technologies for the removal of marine litter in different coastal environments, also assessing their impact on the ecosystems in chosen demo sites and evaluating the economic and societal benefits of the MAELSTROM solutions within local economies. Treatments of the plastic litter for their recovery within a circular economy concept are also foreseen.

The purpose of Deliverable D3.2 is to report on the control with shared autonomy of the Robotic Seabed Cleaning Platform, which is based on cable robotics.

The following videos are attached to this deliverable (cf Section 7 for explanations about these videos):

- https://seafile.lirmm.fr/f/0401ac21e6c74d32ac2b/
- https://seafile.lirmm.fr/f/2feac9b169b844cfb41f/
- https://seafile.lirmm.fr/f/6658db4e6ddf41feae6c/
- https://seafile.lirmm.fr/f/41f9c230bc864aa2add5/

Moreover, the videos of the cleaning campaign in Venice in 2022 are also related to this deliverable since the shared autonomy control of the Robotic Seabed Cleaning Platform described in the present document was improved and tested (see Section 7) during this campaign.

https://youtu.be/1EVQm-0yyRY

https://youtu.be/16k3-Bp4FCI

Co-funded by the Horizon 2020 programme of the European Union

Table of content

List of Figures

Co-funded by the Horizon 2020 programme of the European Union

Co-funded by the Horizon 2020 programme of the European Union

1 Introduction to the MAELSTROM project

MAELSTROM is a project funded under the Topic CE-FNR-09-2020 Pilot action for the removal of marine plastics and litter. MAELSTROM strives to provide answers and diversified solutions to the complex question of the removal and sustainable treatment of marine litter legacy. MAELSTROM contemplates the integration of complementary technologies for marine litter removal in different European coastal ecosystems, compounded with full-fledged circular economy and societal oriented solutions. In particular, the project (i) sets out a reliable multidisciplinary and scientifically sound approach for the assessment of marine debris distribution and impact on marine life in highly valuable ecosystems and protected areas; (ii) designs and manufactures scalable, replicable and automated technologies, co-powered with renewable energy and second generation fuel, to identify, remove and sort marine litter; (iii) evaluates over time the effectiveness of marine litter removal devices along with their impact on local ecosystems; (iv) integrates different technologies to track, sort and recycle all types of collected marine litter into valuable raw materials for future marketisation; (v) assesses the economic and societal impact of the MAELSTROM solutions providing also a comprehensive life-cycle assessment of the technologies and products; (vi) enhances social awareness about the marine litter issue and engages citizens and stakeholders in MAELSTROM activities; (vii) interplays with similar projects to maximize innovation uptake for marine litter removal within and outside the EU.

In particular, MAESLSTROM WP3 aims at developing, implementing and integrating the core technologies for the automated system for seafloor and lower water column ML removal: The Robotic Seabed Cleaning Platform. The technologies pertain to two blocks: (i) the physical structure (T3.1, T3.2, T3.4) and (ii) control/automation system (T3.3, T3.5, T3.6). The present deliverable presents the control system including the sensors used and the shared autonomy.

2 MAELSTROM Consortium

Co-funded by the Horizon 2020 programme of the European Union

	National Research Council	CNR	Project Coordinator Fantina MADRICARDO fantina.madricardo@ismar.cnr.it
	Deltares	Deltares	Frans BUSCHMAN Frans.Buschman@deltares.nl
	University of Malta	UOM	Luciano MULE' STAGNO luciano.mule-stagno@um.edu.mt
	The International Sustainable Development Initiatives	ISDI	Manuel SCARPA m.scarpa@isdigroup.com
	Gees Recycling Srl	GEES	Giorgio BETTETO geesretracking@gmail.com
	Venice Lagoon Plastic Free	VLPF	Davide POLETTO d.poletto@plasticfreevenice.org
	CIMA Research Foundation	CIMA	Isabel GOMES isabel.gomes@cimafoundation.org
	TECNALIA RESEARCH & INNOVATION	TECNALIA	Damien SALLÉ damien.salle@tecnalia.com
	ALPHA Consult	ALPHA UK	Emiliano SPALTRO es@alphacons.eu
	Interdisciplinary Centre of Marine and Environmental Research	CIIMAR	Isabel SOUSA-PINTO ispinto@ciimar.up.pt
	Servizi Tecnici	ST	Nicola FERRARI n.ferrari@stvenezia.com
	The Great Bubble Barrier	TGBB	Philip EHRHORN philip@thegreatbubblebarrier.com
	MAKEEN	MAKEEN	Anders BJORN ABJ@makeenenergy.com
	National Center for Scientific Research	CNRS	Marc GOUTTEFARDE marc.gouttefarde@lirmm.fr

Co-funded by the Horizon 2020 programme of the European Union

3 Aims of the Deliverable

The aim of Deliverable D3.1 is to report on the control with shared autonomy of the Robotic Seabed Cleaning Platform, which is based on cable robotics and on various sensors. Deliverable D3.2 summarises the work done in WP3, in the tasks T3.3 "Underwater perception, Cable robot teleoperated control and preliminary testing", T3.4 "Delivery, Integration and validation of sub-systems" and T3.5 "Cable robot control system improvement - Shared autonomy to improve ergonomics of the pilot station" by the partners, CNRS-LIRMM, TECNALIA, SERVIZI TECNICI and CNR-ISMAR.

The main objectives of each of the aforementioned tasks are the following.

T3.3 Underwater perception, Cable robot teleoperated control and preliminary testing

Task Leader: CNRS; Partners: TECNALIA (M9 - M14)

This task will implement the control system of the cable robot, made of 4 components:

1. The robot teleoperation using devices such as gamepad joystick, remote controller or 3D mouse.
2. Perception system for underwater vision to deliver images of the seafloor to the human operator to ensure proper control of the robot motion (in collaboration with UM). The sensors will be mounted on the cable robot flange and thus be able to operate at close distance (2m and less) to the sea bottom.
3. A collision avoidance algorithm to ensure safe operation of the robot. The latter will compute collision threats based on the current position of the robot end effector and the Digital Terrain Model previously obtained by the multibeam sonar, and it will filter the control of the operator to prohibit motions that would collide with the environment.
4. Partial compensation (based mainly on inclinometers and cable tension measurements) of the movements of the cable robot winches due to swell and waves. This core system made of the teleoperated cable

Co-funded by the Horizon 2020 programme of the European Union

robot with its Perception sensors will be installed in a small version of the T3.2 platform in TECNALIA facilities and Basic technology will be validated prior to shipment to Venice for further integration.

T3.4: Delivery, Integration and validation of sub-systems

Task Leader: ST; Partners: TECNALIA, CNRS, CNR (M15 - M18)

This task will allow all the partners in this WP to deliver, integrate and test their sub-systems into the MAELSTROM Seabed Cleaning Platform. The integration will be performed in ST facilities in Porto Marghera (Venice). Litter will be voluntarily spread under the platform and cleaning capabilities will be demonstrated and validated, prior to deploying the MAELSTROM seabed cleaning platform onto the selected demo sites.

T3.5: Cable robot control system improvement - Shared autonomy to improve ergonomics of the pilot station

Task Leader: CNRS (M15 - M28)

Improvements to the control system will be implemented to reduce the complexity of the robot piloting and associated operator fatigue. The final system will allow the operator to click on the image in the control station to target the area corresponding to litter he wants the robot to remove by suction. The new control system will use a visual-servoing approach to drive the robot autonomously towards the desired target. This advanced control technique will be deployed during the additional cleaning operations performed in WP5.

4 Robotic Seabed Cleaning Platform

The Robotic Seabed Cleaning Platform has been designed, built and tested in Venice lagoon in the framework of MAELSTROM project. Details on its design, testing and installation are given in MAELSTROM Deliverables D3.1 and D5.1. Here, only a brief description of the Robotic Seabed Cleaning Platform is provided.

The Robotic Seabed Cleaning Platform consists mainly of a CDPR installed and operated from a floating barge. The mobile platform of the CDPR can

Co-funded by the Horizon 2020 programme of the European Union

work underwater and is equipped with selective cleaning tools that allow the removal of legacy small (micro-plastics >5 mm) and large items on the seabed, as well as floating plastics in the water column.

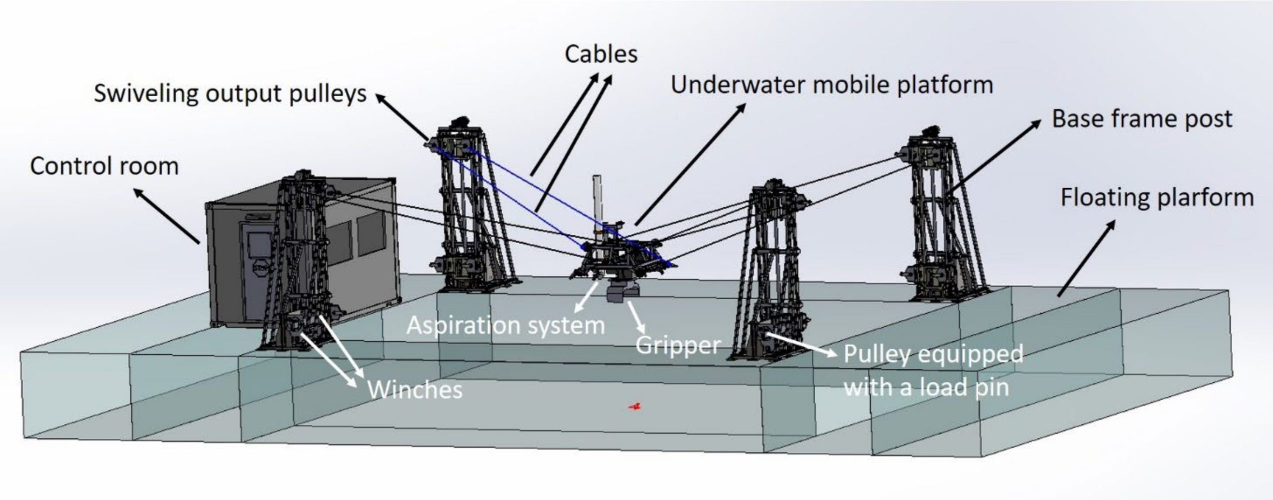
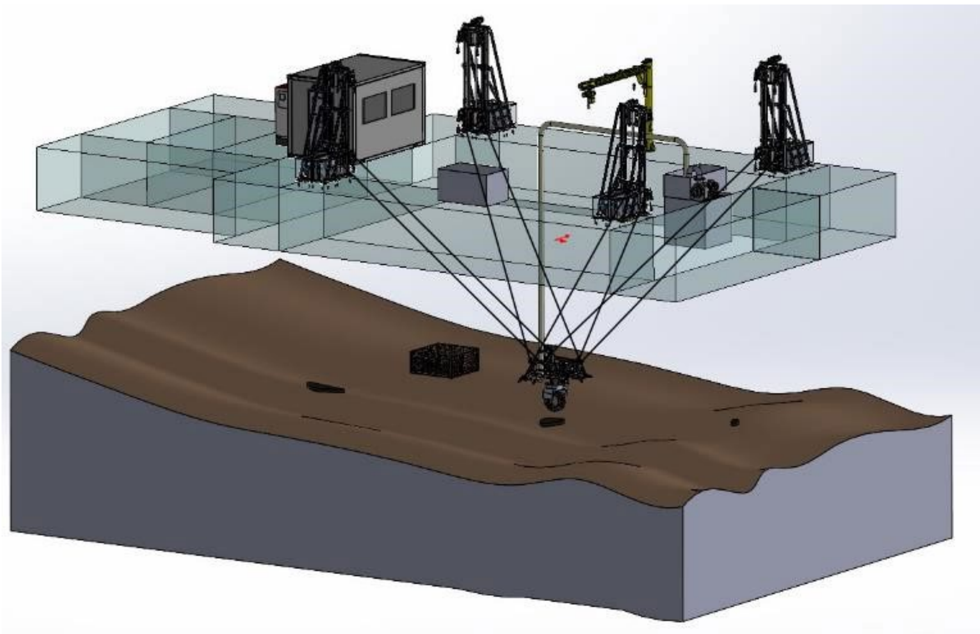


Figure 1 - The main components of the Robotic Seabed Cleaning Platform

The main components of the RSCP are presented in Figure 1 where the mobile platform is shown outside of the water. In the CAD view of Figure 2, the mobile platform is shown working underwater.



Co-funded by the Horizon 2020 programme of the European Union

Figure 2 - A CAD view of the Robotic Seabed Cleaning Platform

with the CDPR mobile platform working underwater

The 6-DOF mobile platform of the Robotic Seabed Cleaning Platform is driven by eight cables in a suspended configuration similar to the one of the CoGiRo, a cable robot previously designed by CNRS-LIRMM and TECNALIA. Four base frame posts are secured to the floating platform (floating barge), the latter being made of several modules (pontoons) assembled together.

Each post has two winches and pulleys that route the cable from the winch to the top of the post where a swiveling output pulley directs the cable toward the mobile platform. One of the pulley located near the winch at the bottom of the post is equipped with a load pin and thereby allows the measurement of the cable tension. The mobile platform can move down in the water below the floating barge which has a rectangular hole (inner pool) in its middle.

An aspiration system to suck up smaller litter in the water column and seabed below the hole in the floating barge, as well as a gripper to remove larger items, are installed on the CDPR underwater mobile platform. A control room hosts the electronic and control cabinets, the control PCs and the human operator(s) of the Robotic Seabed Cleaning Platform.

Co-funded by the Horizon 2020 programme of the European Union

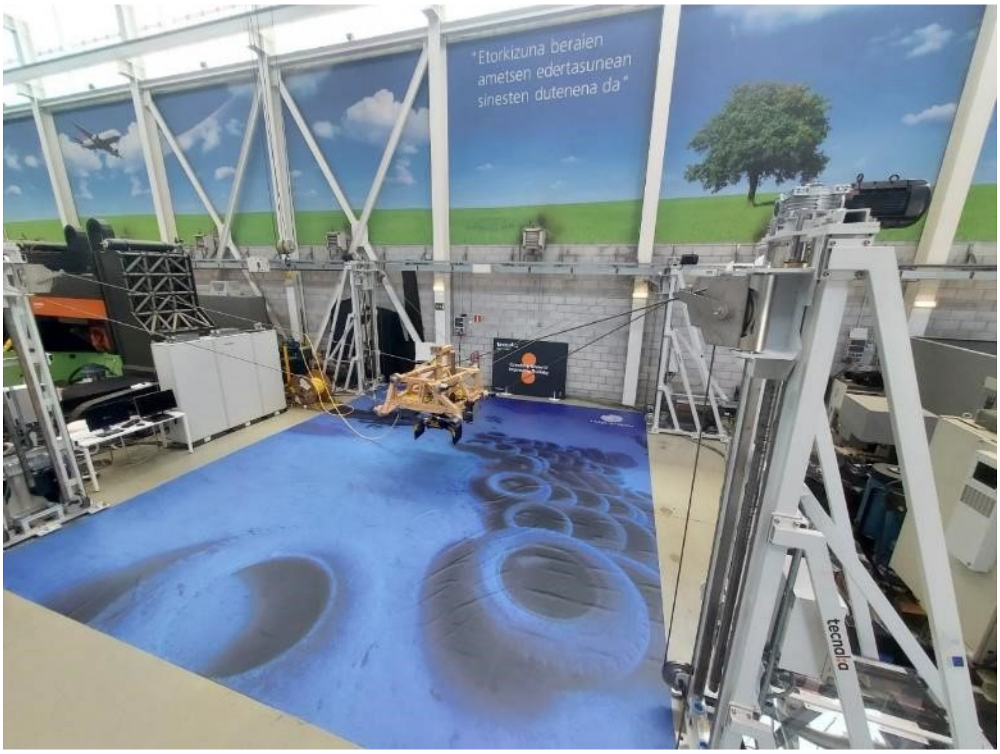


Figure 3 - The Robotic Seabed Cleaning Platform during tests in Tecnalia's facilities

A picture of the Robotic Seabed Cleaning Platform during first tests on the ground in Tecnalia's facilities in Spain is shown in Figure 3. The mobile platform is the beige structure in the middle of the picture. After its setting up in Tecnalia's facilities, the Robotic Seabed Cleaning Platform was disassembled and moved to Venice in Italy for its first underwater cleaning campaign, as shown in Figure 4.

Co-funded by the Horizon 2020 programme of the European Union

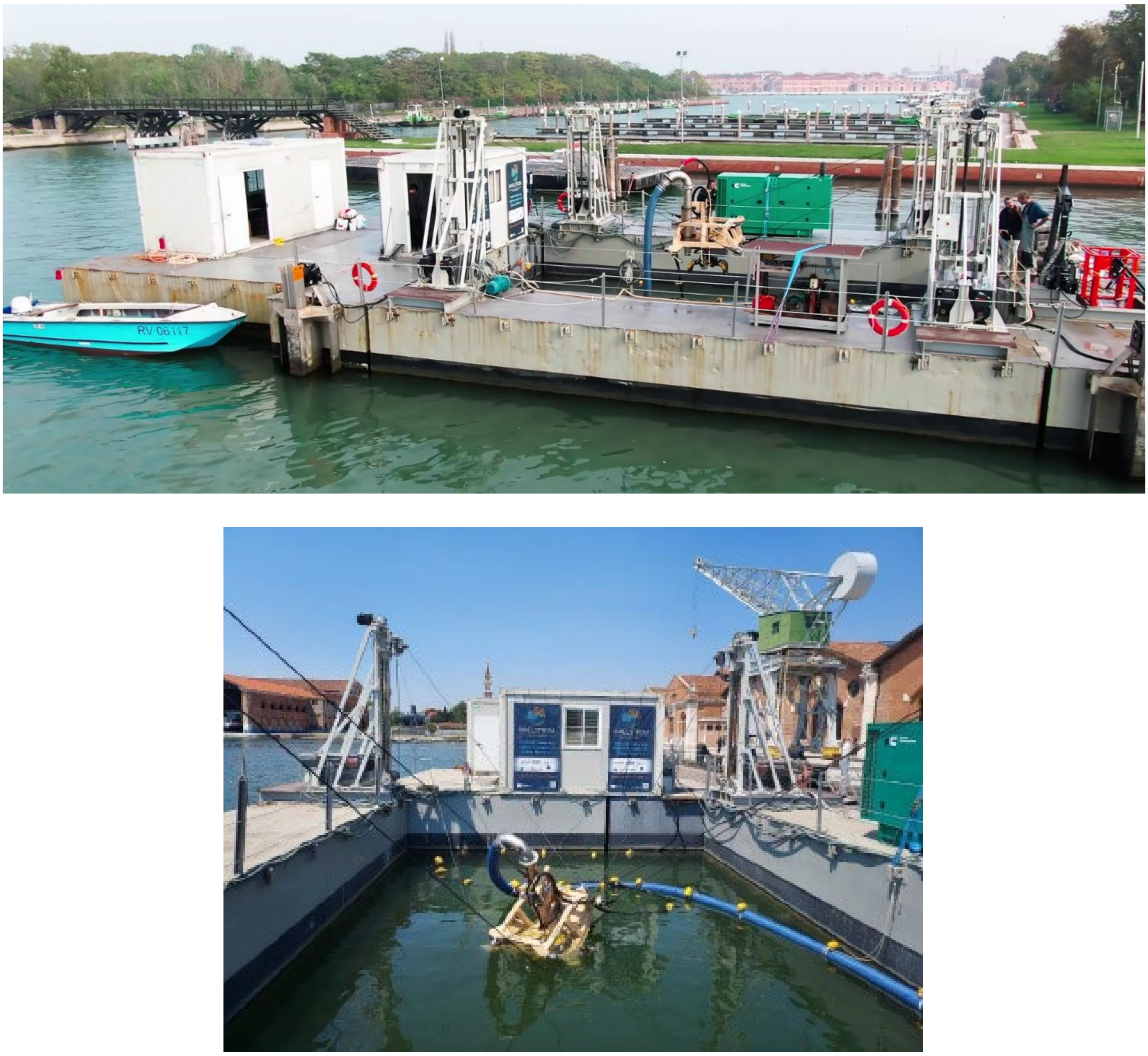


Figure 4 - The Robotic Seabed Cleaning Platform in Venice lagoon.

5 Description of the sensors

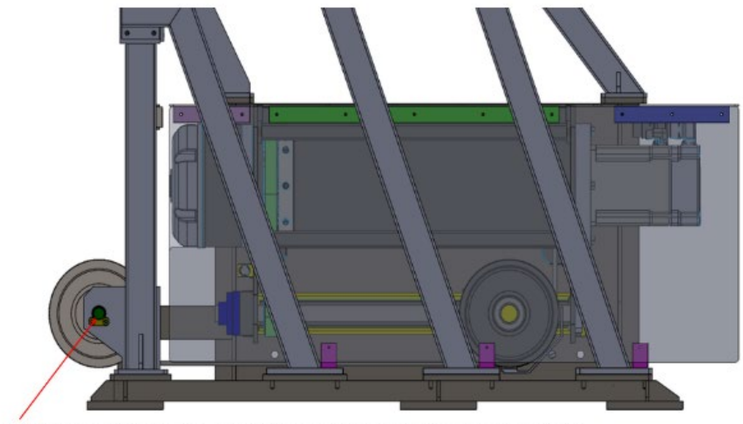
The following sensors are located on the floating platform (floating barge) of the Robotic Seabed Cleaning Platform.

- 2 IMUs integrated in two different posts located on two different pontoons: To measure, at least partly, the motion of the floating platform (triaxial accelerometer, gyroscope and magnetometer

Co-funded by the Horizon 2020 programme of the European Union

providing linear accelerations, angular velocities and attitude measurements).

- Two RTK GPS placed at two different locations on the floating barge to estimate the position (x and y) and orientation (around the vertical axis z) of the floating barge based on Global Navigation Satellite System (GNSS) position measurements[1].
- Eight force sensors to measure the cable tensions (placement shown in Figure 5). These force sensors are essential to the safe operation of the cable robot. The operator should always be able to monitor the values of these tensions to ensure that they do not get too large. Automatic maximum tension values checking is also done in the cable robot control software.
- Encoders in the cable robot winch motors. These encoders are used to in the automatic control the angular positions of the winch drums.
- Acoustic Doppler Current Profiler (ADCP) to measure in 3D the underwater current along the water column (needed in later control developments to plan the grasping, so that the underwater platform displacements are made in the upstream direction with respect to the sea current).
- One pressure sensor to compensate for the atmospheric pressure.



[1] Example device: https://store.arduino.cc/products/arduino-mkr-gps-shield?variant=35572093649047

Co-funded by the Horizon 2020 programme of the European Union

Figure 5 - Location of force sensors in the fixed pulleys

The sensors located inside the underwater mobile platform comprise five IP cameras, as shown in Figure 6 which enable the human operator located in the control room on the floating barge to see the surrounding of the underwater platform (provided that water turbidity is not too high).

Figure 6 - Location of the 5 IP cameras in the underwater robot frame

Several other sensors, listed below, are also integrated into the "smart camera" system shown in Figure 7 and Figure 8. The smart camera system is secured to the underwater mobile platform of the cable robot as shown in Figure 9.

Figure 7 – The waterproof underwater capsule of the smart camera system

Co-funded by the Horizon 2020 programme of the European Union

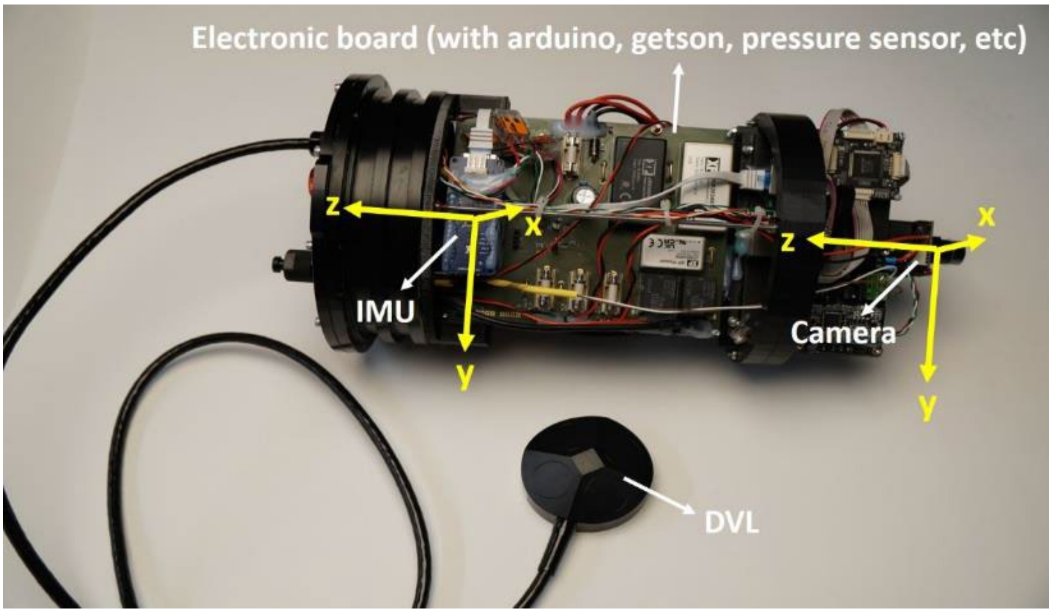


Figure 8 - The smart camera system description and the reference frames fixed to it

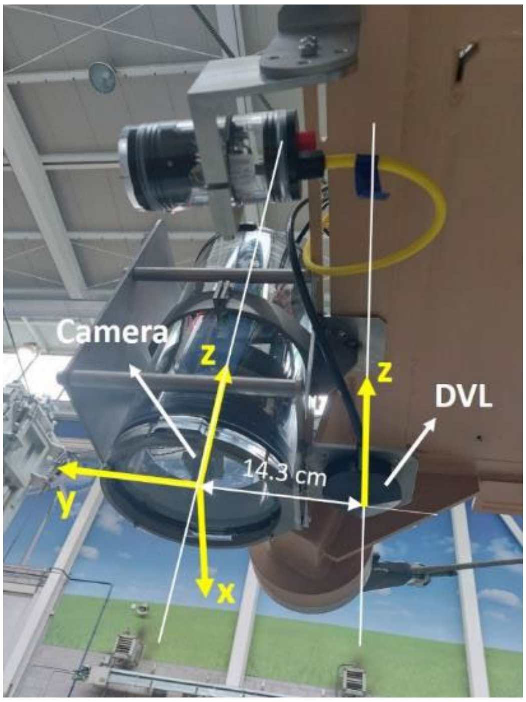


Figure 9 – The smart camera and the DVL on the underwater mobile platform of the cable robot. The coordinate frame attached to the smart camera has the same orientation as the one of the underwater mobile platform

- One camera used for visual servoing: The camera enables a marine litter to be seen by the operator who can click on the litter in the camera image so that the mobile platform of the cable robot approaches

Co-funded by the Horizon 2020 programme of the European Union

the litter automatically. To this end, the camera must be calibrated, for instance using a checker board as shown in Figure 10.

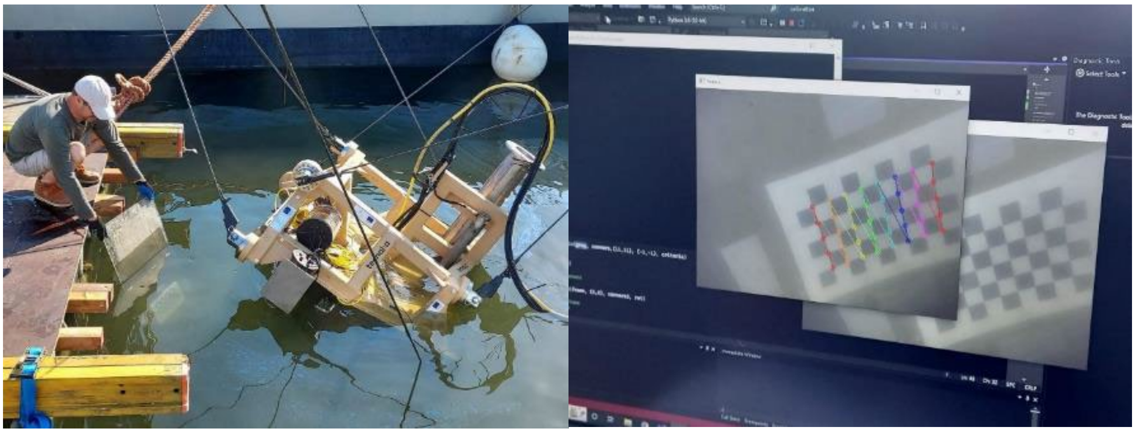


Figure 10 – Calibration procedure of the camera in the smart camera system

- One depth (pressure) sensor[2] to measure the depth of the mobile platform (distance with respect to the seal level).
- One IMU[3] in the smart camera system used mainly to measure the orientation of the underwater mobile platform.
- Doppler Velocity Log (DVL) A50[4] (shown in Figure 11): The DVL is a hydro-acoustic sensor which uses four acoustic beams to measure the distance of the mobile platform to the sea bottom surface and its velocity with respect to the bottom surface. The DVL estimates velocity relative to the sea bottom by sending four acoustic waves from the four angled transducers and then measure the frequency shift (Doppler's effect) from the received echo. By combining the measurements of all four transducers and the time between each acoustic pulse, it is possible to accurately estimate the speed and direction of movement. Since the DVL also indicates the altitude with respect to the sea bottom (from the range measurements achieved by the four beams), it can be used to build a local map of the seabed slope (sea ground surface) such as illustrated in Figure 12. To this

[2] https://bluerobotics.com/store/sensors-sonars-cameras/sensors/bar30-sensor-r1/
[3] https://store.arduino.cc/products/arduino-mkr-imu-shield
[4] https://waterlinked.com/product/dvl-a50/

Co-funded by the Horizon 2020 programme of the European Union

end, the pressure sensors on the floating barge and on the underwater mobile platform can also be used to know the depth of the mobile platform with respect to the floating barge and the altitude of the floating barge with respect to the sea bottom surface. Subsequently, the two GPS on the floating barge can be used to locate the local map in a global earth coordinate system. This allows either estimate the position of underwater litters previously located and/or to build a map of the (removed) litters.

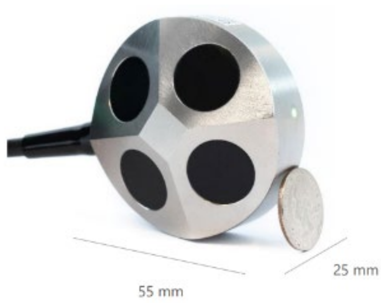


Figure 11 – The DVL Waterlinked A50; Important notice: The DVL must remain in water to ensure sufficient cooling when doing development with the DVL.

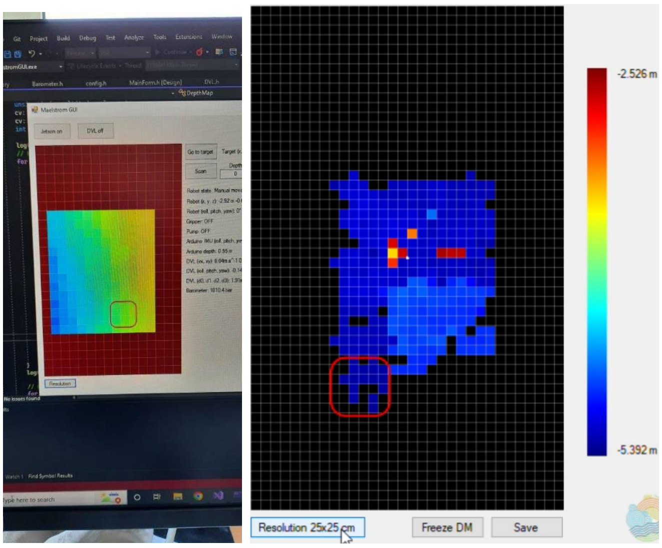


Figure 12 –Examples of bathymetry map obtained by means of the DVL placed on-board the underwater mobile platform

Co-funded by the Horizon 2020 programme of the European Union

6 Control system of the robotic seabed cleaning platform

The control system of the cable robot is made of four main components:

1. The cable robot teleoperation control;
2. Perception system for underwater vision;
3. Collision avoidance module;
4. Partial compensation module.

These four components are described in the following sections.

6.1 Cable robot teleoperation control overview

As shown in *Figure 13*, two computers (CDPR iPC and PC2) are used to control the cable robot and to handle the date of the various sensors. The data of the sensors located on the underwater mobile platform are transmitted to the surface (control room) by means of an umbilical cable. All the sensors and communication data on the surface are shared between the PCs and cable robot drivers by means of an Ethernet network. To speed up communication between the two PCs (pseudo real-time communication), an UDP communication link is established.

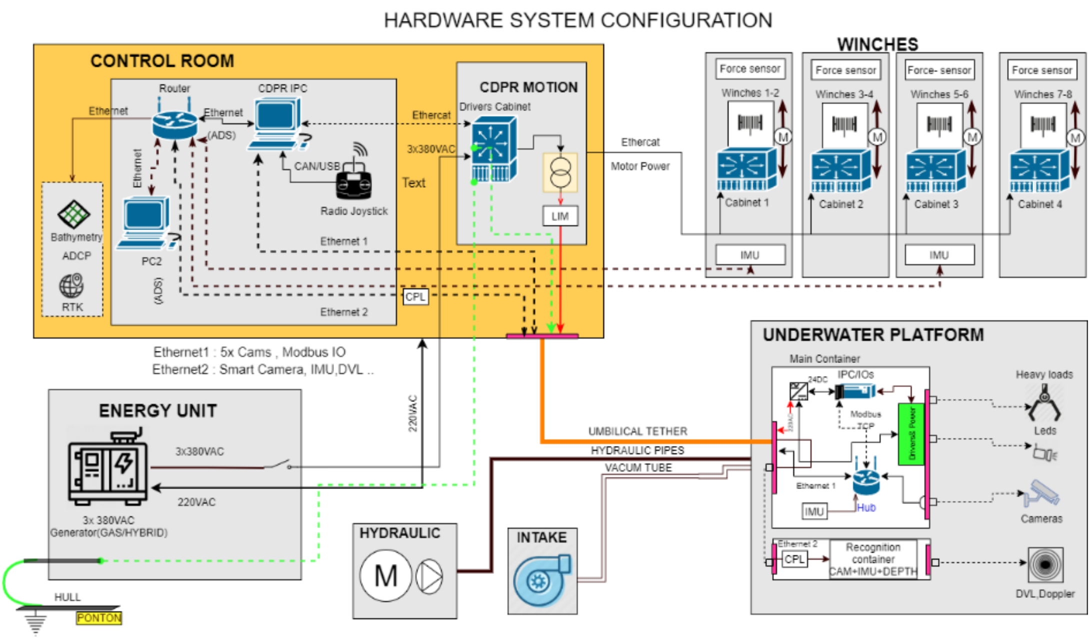


Figure 13 – The overall layout of the hardware

Co-funded by the Horizon 2020 programme of the European Union

Figure 14 - Radio controller of the cable robot

The pilot (human operator) uses estimated underwater mobile platform position as well as the cameras located on the mobile platform to drive the underwater mobile platform using a joystick (radio controller shown in *Figure 14*). The joystick commands issued by the pilot are interpreted as desired operational velocities, i.e., linear and angular velocities of the underwater mobile platform. These velocities are integrated to provide desired positions and orientations of the mobile platform that are converted into desired winch motor positions by means of cable robot inverse kinematics (see below). These desired joint motor positions are sent on the fly to the drive setpoint controller which is in charge of the feedback position control of the motors.

Cable robot inverse kinematics

The inverse kinematics consists in calculating the winch motor positions (angular rotations of the motors and thus of the drums) from the knowledge of a desired position and orientation of the underwater mobile platform.

Because high accuracy is not needed in teleoperation control since the human operator has visual feedback from the cameras placed on-board the mobile platform, the cable elongation due to strain (cable tension) can be neglected. In the following, the cable elongations are thus neglected so

Co-funded by the Horizon 2020 programme of the European Union

that the inverse kinematics is a purely kinematic problem (no forces involved).

The basic knowledge needed are the positions of the cable attachment points Bi on the mobile platform expressed in the coordinate frame attached to the mobile platform as well as the positions of the points Ai wherefrom the cables exists the swivelling pulley on the metallic posts of the supporting structure (exit points). The fixed reference coordinate frame (Ob,x,y,z) attached to the floating barge is shown in Figure 15 and Figure 16.

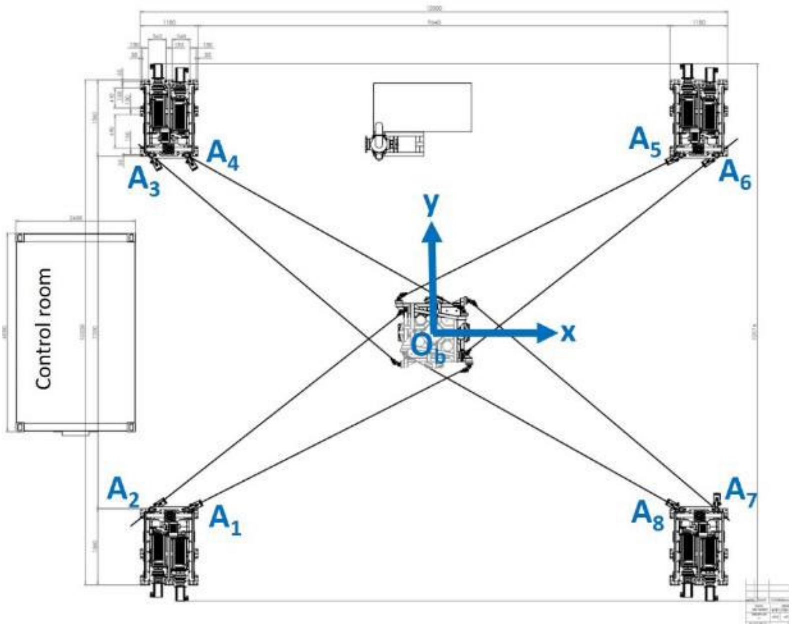


Figure 15 – Definition of the floating platform reference frame and cable exit points Ai (top view)

Co-funded by the Horizon 2020 programme of the European Union

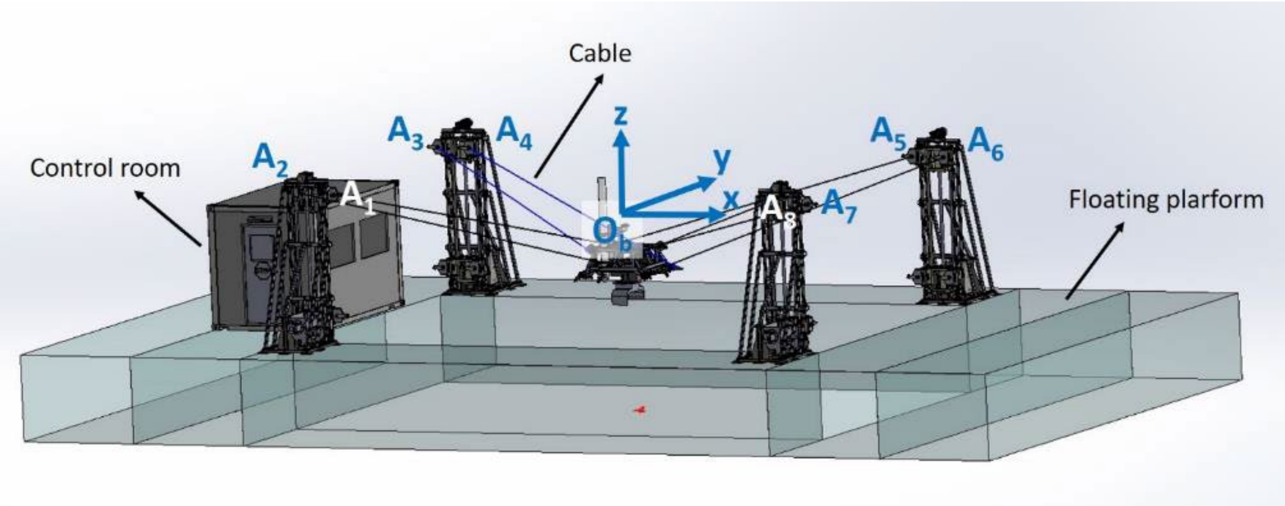


Figure 16 – Definition of the floating platform reference frame and cable exit points Ai (perspective view)

The underwater mobile platform reference frame (Op,x,y,z) is shown in Figure 17. This figure also shows the cable attachment points Bi on the mobile platform. The origin Op of the mobile platform reference frame is located at the center of the straight-line segment between the attachment points B1 and B5.

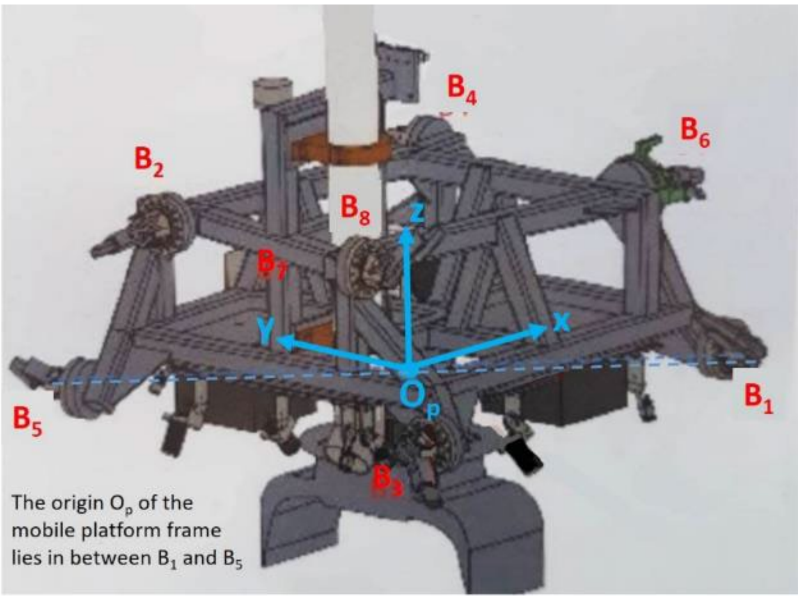


Figure 17 – Underwater mobile platform reference frame and cable attachment points Bi

Co-funded by the Horizon 2020 programme of the European Union

MAELSTROM

Based on these data, being given a desired position and orientation of the mobile platform, i.e., a desired position and orientation of the mobile platform frame (Op,x,y,z) in the floating barge reference frame (Ob,x,y,z), the positions of the cable attachment points Bi in (Ob,x,y,z) can be calculated. Then, considering the swivelling pulley kinematics[5] (radius of the pulleys is equal to 120 mm), the lengths of the cable segments from Bi to Ai can also be calculated. Moreover, being given the primitive diameter and pitch (equal to 227 mmm and 13 mm, respectively) of the winch grooved drum, these cable lengths allows one to calculate for each winch the required drum angular position (provided that the position and orientation of the mobile platform in its parking or working pose, or any other calibration pose, are known from measurements). Finally, using the gear ratio between the motor and the winch drum (equal to 64.155), the motor angular position can be obtained from the drum angular position thereby completing the inverse kinematics computations.

MAELSTROM web-based cable robot HMI (Client/Server architecture).

The Human-Machine Interface (HMI) of the cable robot designed by TECNALIA is shown in Figure 18. It allows the human operator (pilot) to monitor various sensor values and to choose between different control modes.

[5] The calculation of the kinematics of cable robots taking into account pulley kinematics is well-known in the state of the art, e.g., in Section 7.2 of the book "*A. Pott, Cable-driven parallel robots, Springer, 2018*".

Co-funded by the Horizon 2020 programme of the European Union

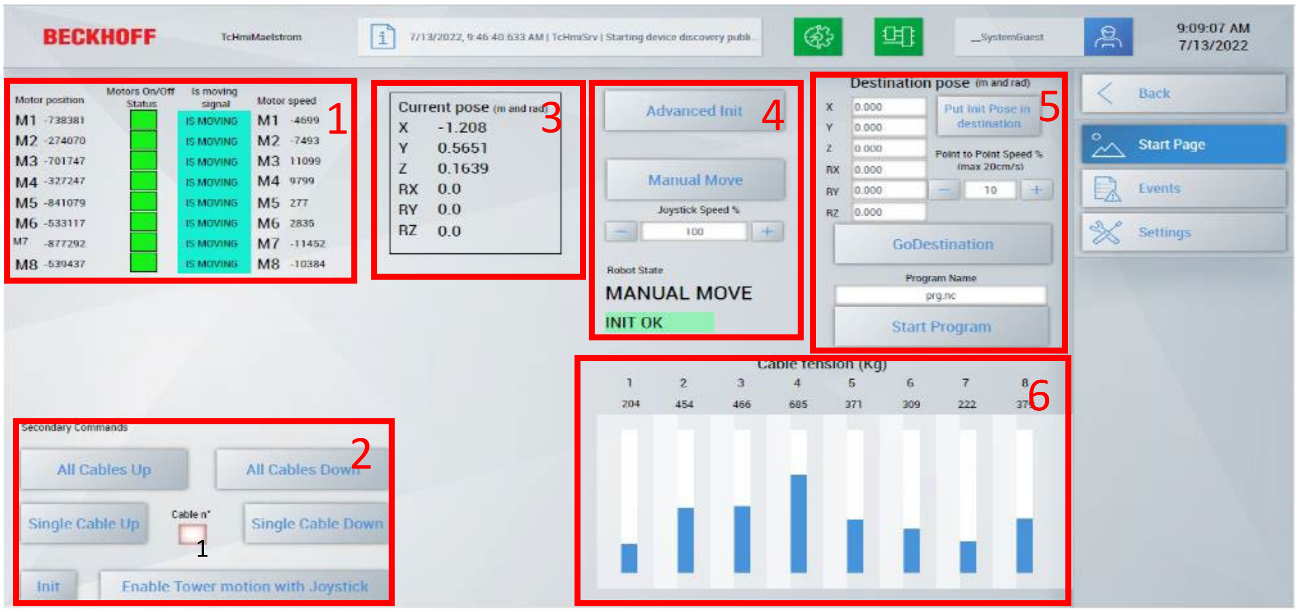


Figure 18 - Cable robot HMI (TECNALIA)

Cable robot HMI DESCRIPTION:

1. Winch axis information area: Motor encoder position, speed, power and motion status.
2. Secondary commands: These command buttons are for setting up:
    - Individual or combined motion of the cables without transformation activated;
    - Motion command to calibration position (Init);
    - Enable post linear axis movements using the joystick.
3. Robot pose (position and orientation) information area: Relative to robot reference frame (floating platform coordinate frame) in meters and radians.
4. Manual commands area including:
    - Initialization: Calculation of the Cartesian pose (computed using the winch motor positions by means of forward kinematics);
    - Manual move with joystick enabling & speed override setting;

Co-funded by the Horizon 2020 programme of the European Union

- Robot status.

5. Automatic command area including:

- PTP motion command (actual to destination pose);
- CNC trajectory program execution.

6. Cable tension monitoring area: Force sensor values in Kg.

The human operator can see the videos from the IP cameras placed on-board the underwater mobile platform in a dedicated screen (Figure 19).

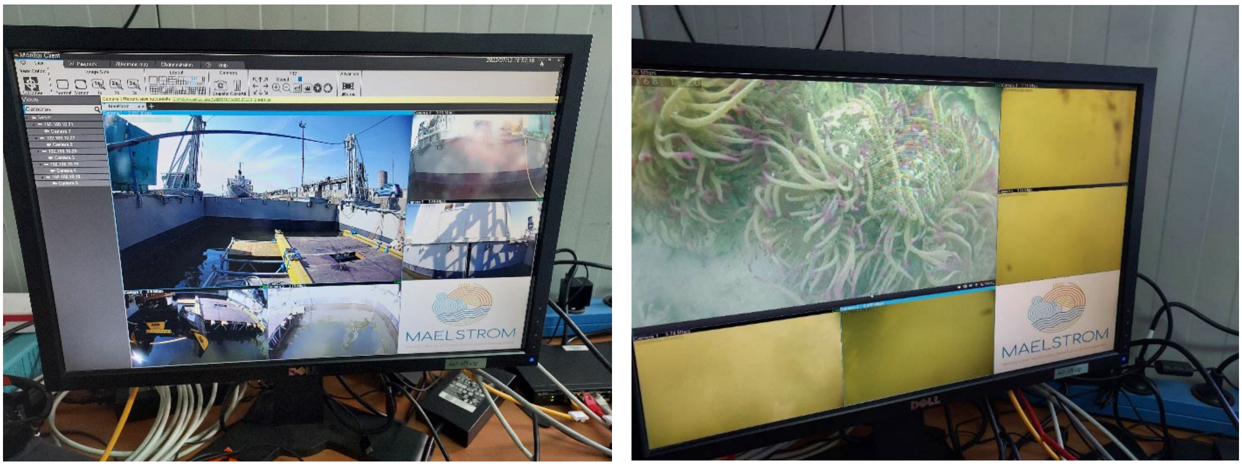


Figure 19 - Screen showing videos of IP cameras: Outside of water (picture on the left) and in Venice lagoon turbid water (picture on the right)

6.2 Perception system for underwater vision

The camera in the smart camera system (Figure 8) is used as the underwater perception system. It notably enables visual servoing: Once a marine litter is seen by the human operator (at relatively closed range from the camera because of water turbidity), the latter can click on the litter in the camera image and the mobile platform of the cable robot approaches the litter automatically. To this end, the camera must be calibrated, for instance using a checker board as shown in Figure 10. Once the camera is calibrated, the position of the litter in the image can be obtained. Being

Co-funded by the Horizon 2020 programme of the European Union

MAELSTROM

given the position and orientation of the coordinate frame attached to the camera in the underwater mobile platform reference frame (Op,x,y,z), the position of the litter in (Op,x,y,z) can be obtained. Then, from the knowledge of the position and orientation of the mobile platform in the floating barge reference frame (Ob,x,y,z), the position of the litter (Ob,x,y,z) can also be obtained. From one of these two position calculations, a simple interpolation can be made to calculate the motion of the mobile platform needed to move toward the litter.

The Figure 20 below shows the Graphical User Interface (GUI) of the underwater perception system. On the left, the depth map built with the DVL measurement is shown. In the middle, the human operator can see the image from the camera of the smart camera system (here shown in turbid water with very little visibility range). The operator can click on a point in this image, where a possible litter to be removed is located, so that the mobile platform moves toward this point.

On the right of the HMI, the bathymetry map is shown. It is centered on the RSCP inner pool (the orange rectangle). The red rectangle is the safe working zone where no collision between the RSCP and the CDPR cables can happen. In the HMI bottom part, various sensor values and other information are displayed.

Co-funded by the Horizon 2020 programme of the European Union

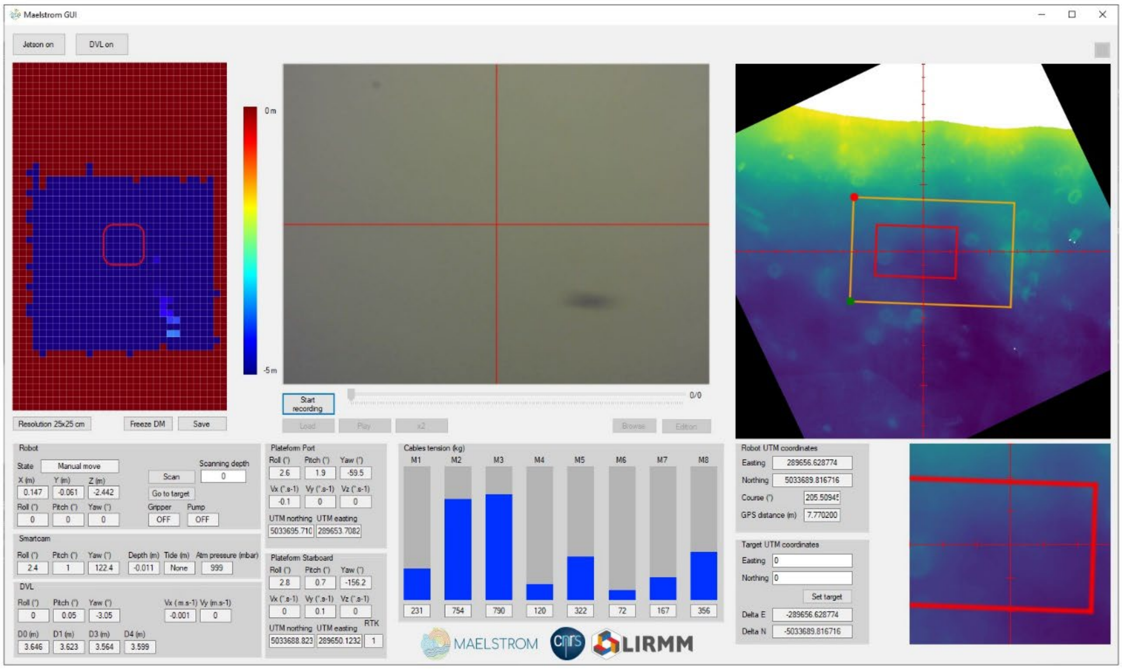


Figure 20 – GUI of HMI of the underwater perception system (smart camera, DVL, depth sensors and various data from the cable robot control system)

6.3 Collision avoidance module

The collision avoidance module aims at ensuring safe operation of the cable robot. A first version of the corresponding software has been developed in Unity[6] and .net in C# language. A screenshot is shown in

[6] Software platform for real-time animation including collision checking (fast distance computations), https://unity.com/

Co-funded by the Horizon 2020 programme of the European Union

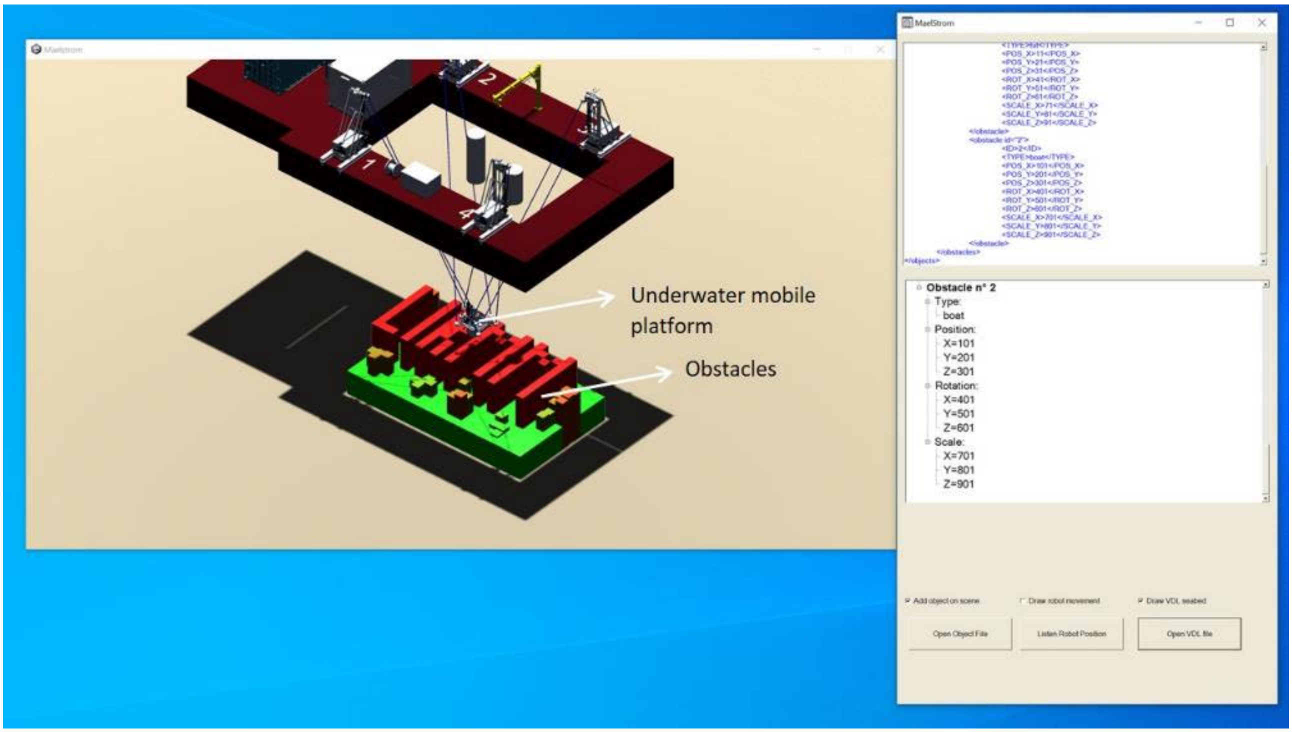


Figure 21 – Screenshot of the collision avoidance software developed in Unity and .net in C# language

Since the cable robot mobile platform moves underwater, the operator may have limited visual feedback on its position and of surrounding objects. He/she can hardly anticipate the risk of collision with a possible obstacle or to have an estimation of the distance to a litter to be removed. Hence, providing an HMI that allows the operator to have a feedback on what is happening underwater may be important. To this end, our choice was a hybrid development consisting of:

- .net in C# language for the dialog box for the operator, communication with the robot, management of litter / obstacles;

- Unity in C# language (3D/physical engine) for:

  - 3D graphical display (floating barge, cable robot mobile platform, obstacles, representation of data obtained by robot, ...);
  - Management of platform collisions with obstacles (barge, bottom, obstacles, ...);
  - Management of cable collisions with obstacles or other cables (where the cables are considered as being straight line segments);

Co-funded by the Horizon 2020 programme of the European Union

- All in real time.

To date:

- The hybrid application between dialog box (Windows standard) and Unity is functional.

- The 3D graphic display from Solidworks CAD is functional.

- Display of waste/obstacles generated from a database (in XML form) is functional.

- Display of the background according to data obtained by bathymetry is functional.

- Collision management between platform and objects is working. If a collision is close to happen, a sound and a visual alarm warn the operator.

- Collision management between cables/cables or cables/objects is working (audible and visual alarms).

- Projection of the platform according to its speed in order to anticipate collision is functional.

The following items remain to be done.

- Test speed projection according to robot data;

- Test representation of the underwater scan (bathymetry).

- Make dynamic repositioning of the barge/robot in real time according to robot data.

These items have been partly tested during the testing in Venice in 2022 but, since the collision avoidance module was not a priority (not needed during the experiments and the DVL broke down during the experiments, the full testing of these items remain to be done.

6.4 Partial compensation module

The goal this module is to compensate, using the cable robot winches, the undesired movements of the cable robot mobile platform due to swell and

Co-funded by the Horizon 2020 programme of the European Union

waves acting on the floating barge. It should be based on the two IMUs placed on the floating platform and on cable tension measurements. This module has not yet been implemented because during the experiments and cleaning campaign made in 2022 in Venice with the Robotic Seabed Cleaning Platform, there was no need of movement compensation. If required, measurements will be made and then analysed during the next tests and cleaning Campaign in Venice in 2023. Based on these possible measurements, strategies to compensate the undesired movements may be proposed. Potential challenging issues are the quality of the data obtained from IMU measurements and the limited dynamics of the winches with respect to that of the undesired floating barge movements.

7 Details on the shared autonomy

The overall goal is to endow the control system will tools and capabilities enabling to reduce the complexity of the robot piloting and associated operator fatigue.

7.1 Summary of the litter removal process

This section summarizes the litter removal process during the cleaning campaign with the Robotic Seabed Cleaning Platform in Venice in 2022.

First, a location is selected with the help of the bathymetry provided by the CNR. The objective is to find an interesting zone where large litters can be seen on the bathymetry, and to move the floating barge to the corresponding GPS coordinates.

As soon as the barge arrived to the desired location, a scan is performed with the DVL at sea level. The scan gives an accurate mapping of the zone, offering a reliable and real-time feedback to the operator. Once the scan is done, the robot can move freely within its safe working zone, as every dangerous object (i.e. large objects that could collide with the robot) are detected and projected on the Graphical User Interface (GUI) depth map (Figure 20).

Co-funded by the Horizon 2020 programme of the European Union

A second underwater DVL scan is then performed closer to the seabed, using the prior scan to move close but above the seabed, allowing for better resolution mapping, but also for more visibility on the potentially lying litter. While the robot is scanning the zone for the second time, the operator can safely click on the image (within the GUI) where he sees macro litter. Each time the operator clicks on the image, the depth (given by the depth map) and the 2D coordinates of the clicked pixel are saved.

Finally, once this last scan is completed, the robot can automatically move a few centimetres above the saved coordinates, giving a complete view of the previously seen object and letting the operator grab or suck the macro litter. The grabbed object can then be retrieved on the barge, and the robot can automatically move to the next litter lying on the seabed.

7.2 Visual servoing

First and foremost, the smart-camera is calibrated underwater with a checkerboard (see Figure 10). The intrinsic parameters, such as the optical point, the focal length, and the skew, and extrinsic parameters, which transform a 3D world point to the 2D camera coordinates, are then computed. Then, being given a 2D point on the camera coordinates, and its depth (given by the DVL which is rigidly attached to the smart camera, see Figure 9), we can determine the 3D position of an object. The 3D position is then send to the robot, which calculate the trajectory.

Although the visual servoing has been implemented and tested on ground (see video: https://seafile.lirmm.fr/f/0401ac21e6c74d32ac2b/),the high turbidity of the water in Venice lagoon made impossible for the operator to identify clearly any litter within the image.

7.3 Depth map and high turbidity

The DVL scan has been tested for the first time in Port Marghera (Venice). Figure 22 shows the first version of the GUI and the resulting depth map (see video: https://seafile.lirmm.fr/f/2feac9b169b844cfb41f/).

Co-funded by the Horizon 2020 programme of the European Union

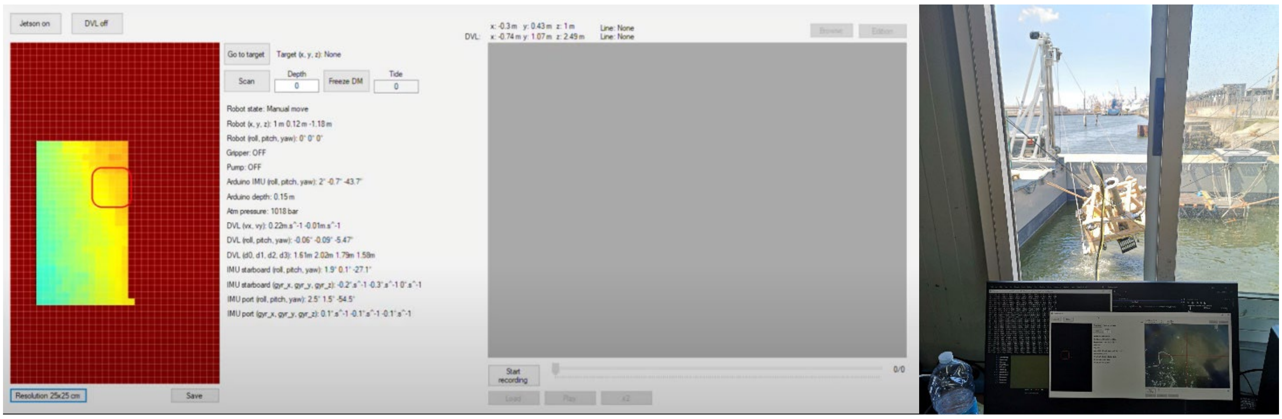


Figure 22 – First test/implementation of the DVL scan in Port Marghera (Venice)

While the operator moves the robot (represented with the red square in the depth map), the GUI software records the four beams signal of the DVL and, knowing their orientations, projects them into the depth map. The depth shown in Figure 22 suggests a light slope, which is confirmed by the barge location. Indeed, the barge was docked on the side of the canal bank, which explains this slope.

The next day of these tests in Venice, the barge moved to the Arsenale to perform further tests before the first cleaning campaign. At this stage, the GUI uses the 2 RTK-GPS antennas (located on both the barge port and starboard sides) data to compute the position of the barge with respect to the global map origin. The global map origin is defined as the geographic point located at distance chosen to be 50 meters away in the North-West direction, starting from the position of the port GPS antenna, when a new map is requested. The global map axes are in the range [0, 100 m] and are oriented respectively to the East (x-axis) and to the South (y-axis). The update rate of the RTK-GPS is 1 Hz, but this should be increased, if possible, to smoothen the position noise (less than 5 cm during July 2022 experiments in Venice).

Hence, each beam is geo-localized in the global map, allowing the barge to drift while keeping track of the depth map (see video: https://seafile.lirmm.fr/f/6658db4e6ddf41feae6c/).

Co-funded by the Horizon 2020 programme of the European Union

Figure 23 shows the resulting mapping for two different resolutions (5x5 cm and 25x25 cm, upper image). Interestingly, a squared object emerges from the depth map, which suggests that one of the "blocks" lying on the seabed, shown by the red circle on the bathymetry image (lower image of Figure 23) has been flown over by the robot.

The high water turbidity, which leads to very poor visibility, restrains the camera usage since the operator could see barely anything on the image. Although we enhanced the image by applying an adaptive histogram equalization (CLAHE), strong limitations in visibility range were still present.

Therefore, we decided to use a low resolution (i.e. 25x25 to 50x50 cm) for the first scan, and then use a high resolution (5x5 cm) hoping to draw the shape of medium to large objects in the depth map. This idea was tested with the block shown in red in Figure 23.

Co-funded by the Horizon 2020 programme of the European Union

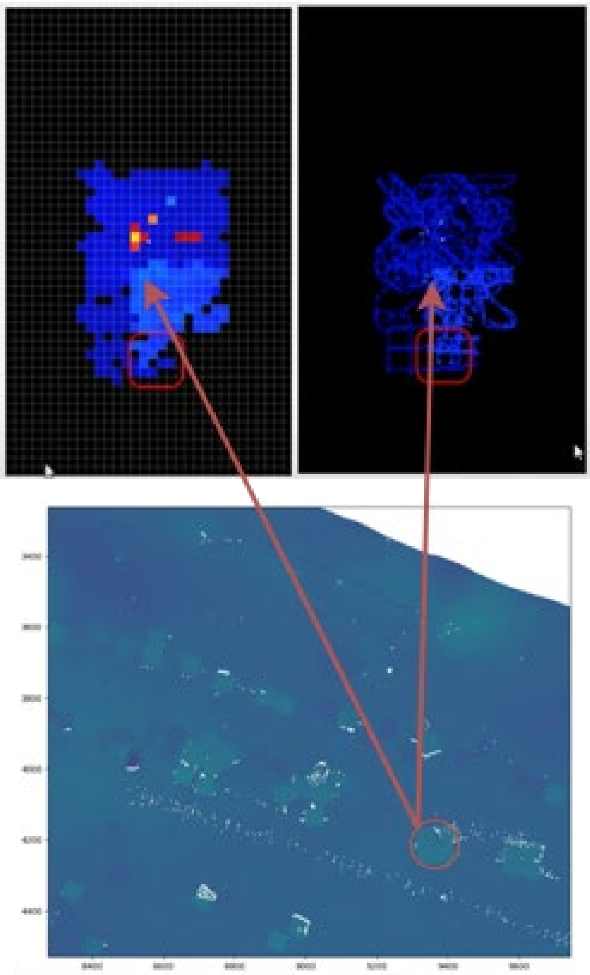


Figure 23 – DVL mapping at two different resolutions (upper image) and the corresponding bathymetry (lower image)

7.4 Tide estimation and depth compensation

As the tide was changing relatively slowly in Venice lagoon during the experiments in July 2022, we decided to estimate the tide with the DVL.

Once the first scanning is completed, the current depth map is saved as a a reference for tide estimate. Subsequently, the tide is estimated in real-time, with respect to the initial map, by comparing the current height of the water column, i.e., the sum of the altitude given by the barometer on the floating platform, and the smart-camera depth with the initially measured height (i.e. value stored in the initial depth map). This tide

Co-funded by the Horizon 2020 programme of the European Union

value can then be used to compute the tide-compensation values of the depth map.

7.5 DVL workaround and bathymetry implementation

Unfortunately, the DVL broke down the next day without letting any possibility of quick reparation. As we did not start the cleaning campaign yet, we had to quickly find a workaround.

First, we chose to test the accuracy of the floating barge GPS position with respect to the bathymetry map. To this end, we chose the GPS coordinates of one of the blocks visible in the bathymetry (as illustrated in Figure 23), and try to place the end-effector of the robot at the same location. As the result appeared to be accurate enough (approximatively less than 5 cm error between the two), we decided to implement the bathymetry directly into the GUI as shown in Figure 24. As shown by red arrows in Figure 24, we can see numerous objects, resembling tires, lying on the seabed on the bathymetry image. Given the null visibility and the DVL breakage, the operator used the bathymetry only to pilot the robot (see video: https://seafile.lirmm.fr/f/41f9c230bc864aa2add5/).

In the bathymetry, the orange rectangle represents the inner pool of the barge, i.e., the rectangular hole allowing the mobile platform of the cable robot to dive in the water. The red rectangle represents the safe working zone of the robot where no cable collision with the barge can happen, and the scaled cross at the center of the image represents the robot position.

We decided to rotate the image with respect to the barge course but also the robot coordinate system to help the operator, so that the operator joysticks and the image are oriented in the same way.

Moreover, although we could not use the visual servoing because of high water turbidity, we added the possibility for the operator to enter desired GPS coordinates and send the cable robot mobile platform to these coordinates automatically.

Co-funded by the Horizon 2020 programme of the European Union

Hence, finally, the fact that the DVL broke down, the cleaning campaign was finally performed using a bathymetry approach and this was a good experience and we ended up using only the bathymetry approach.

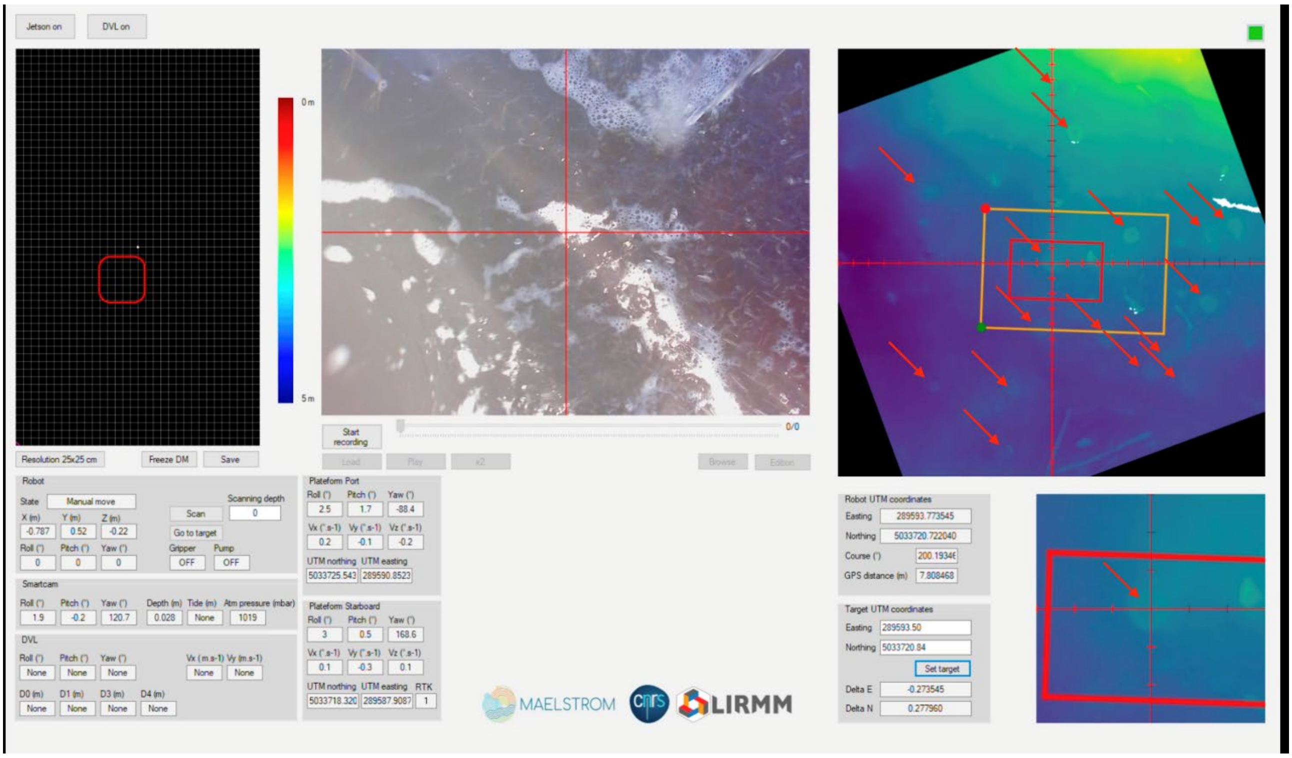


Figure 24 – The full GUI of the underwater perception system used in Venice during the first cleaning campaign in 2022. The red arrows show objects on the bathymetry image that could be tires.

Co-funded by the Horizon 2020 programme of the European Union

MAELSTROM

8 Conclusion

This deliverable presented the control with shared autonomy of the Robotic Seabed Cleaning Platform. The latter mainly consists of a cable robot installed on a floating barge. The floating barge can be displaced with a boat to a desired location where underwater litter is possibly located. The cable robot mobile platform can then move underwater to grab or suck litter and thereby remove it from the water. The cable robot mobile platform is teleoperated by an operator (pilot) with a joystick and with the help of various means of shared autonomy. The first means is the cable robot inverse kinematics that allows mapping the operator joystick commands (mobile platform velocities) into synchronized winch motor movements that result in the desired Cartesian motion of the cable robot mobile platform. For global positioning of the floating barge, GPS localization is used. By means of bathymetry maps previously obtained and two RTK GPS on-board the floating barge, the latter can be moved above desired underwater locations where litter may be located. Then, visual servoing (provided water turbidity is not too high) and/or local seabed map (built with DVL acoustic measurements) are provided to the operator to enable him/her to move the underwater mobile platform very close to the desired location. The operator can then look for a possible underwater litter by means of vision (cameras) and remove it from the water.

Co-funded by the Horizon 2020 programme of the European Union