Smart and Networking Underwater Robots in Cooperation Meshes

SWARMs Newsletter #2 **January 2017**

SWARMs Early Trials

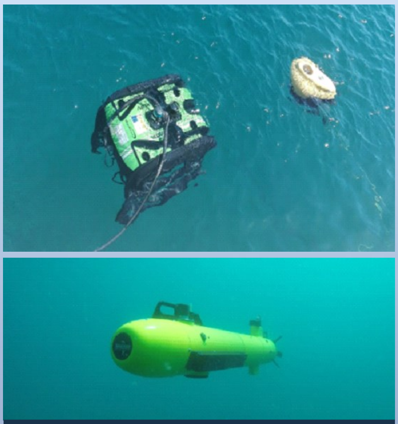
The first stage of field trials and demonstrations planned in the SWARMs project was held during the last weeks of September 2016. These Early Trials took place at PLOCAN facilities in Gran Canaria island (Spain) with a duration of 10 days of exhaustive proofs of concepts and validations of the technical developments made during the first year of the project.

In order to address the different challenges within the project, a series of seven different missions were executed as previously planned. These missions were essentially split according to the respective domains and involved technologies, i.e. Environment sensing, Communication, Simulation and Middleware (MW):

Mission 1: Bathymetric sensors and seabed mapping
Mission 2: HF modem data transfer
Mission 3: USV-Shore communication
Mission 4: AUV-ASV communication
Mission 5: Simulation of ROV-Shore-USV data transfer
Mission 6: Simulation of models for vehicles, sensors and manipulators
Mission 7: Mission planning with several vehicles

The fruitful collaboration among partners participating in the trials produced a high quality set of results aligned with the SWARMs objectives defined for the Atlantic Ocean Validation milestone, which were directly related to the effective testing of devices or technological developments carried out in the first year of the project. A plethora of useful information was collected during the Early Trials, not only in terms of data but also concerning integration and testing procedures, as well as good practices, to be further exploited in the next validation milestones at the Black Sea (Romania) and at the Norwegian coast.

SWARMs team at the Early Trials



Two vehicles used in the Early Trials

1st Stage integration

To proceed with demonstration activities, a first stage of integration will be held in the first half of 2017, culminating at the Black Sea, in Romania. The aim is to integrate, within the participant vehicles, several developments from SWARMs working together.

Further in this issue

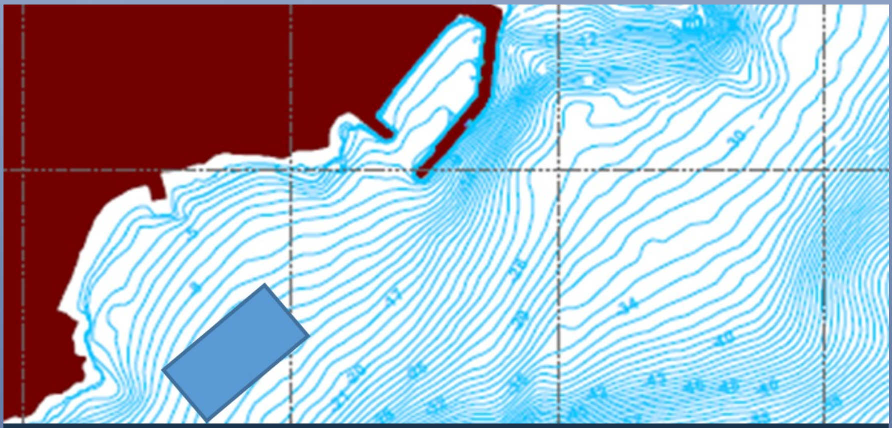
Environment sensing

One of SWARMs main goals is to define the sensors and information processing framework that will allow the perception of the existing environment and therefore provide more autonomy to the vehicles, allowing them to perform more complex tasks and, when a completely autonomous operation is not feasible, appropriately simplify the information so that it can be exchanged with an external operator.

During the first year of the project the main focus has been given to different types of sonars suitable for large scale mapping, such as side-looking and forward-looking sonars, as well as different types of optical sensors suitable for close range inspection, such as stereovision cameras, and algorithms for automatically extracting information from sensor datasets and merging different types of maps.

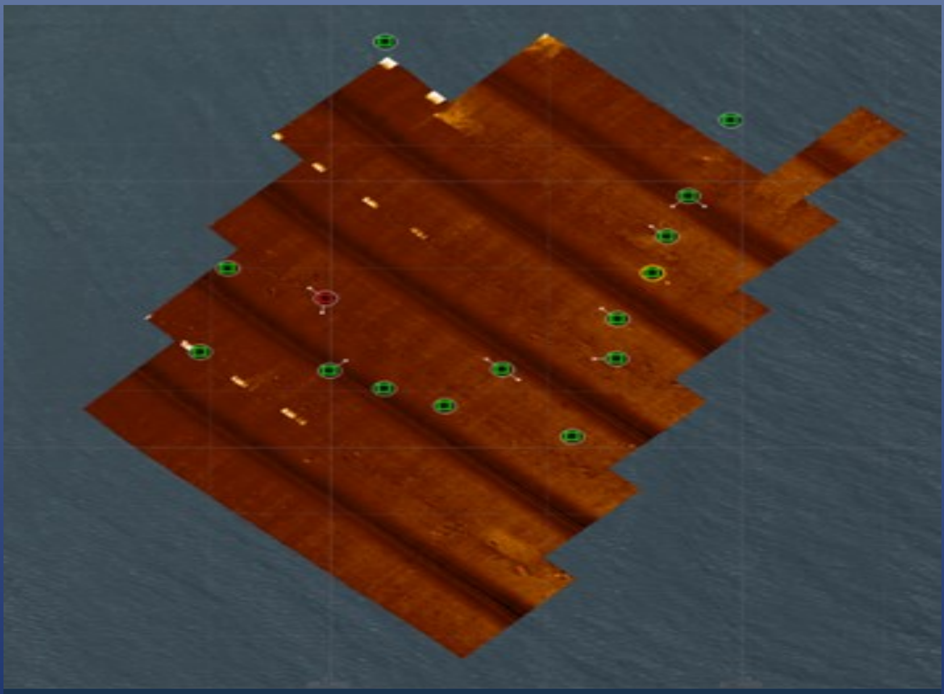
Both acoustic and optical sensors were successfully tested during the Early Trials conducted at PLOCAN's facilities. The Klein 3500 bathymetric side-looking sonar was successfully integrated in the ECA A9 AUV and tested in a shallow water test site in Melenary Bay, at Gran Canaria island. The reflectivity and depth maps were processed offline for quality assessment and feature extraction. The extracted features were afterwards used to cue the Desistek SAGA ROV, equipped with forward-looking sonar and video, for detailed inspection of those features.

ECA A9 and Desistek SAGA

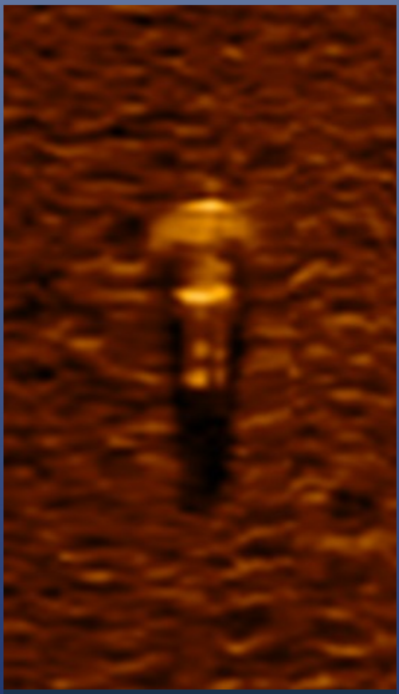


Map of testing region, including survey area represented by blue rectangle

SAGA video image of a landmark



Constellation of landmarks detected automatically using an algorithm developed by ECA



Detail of landmark in A9 sonar image

Communication subnetworks

The sea is a harsh and challenging environment for communication systems, both in air and underwater:

- Its surface acts like a mirror, reflecting both RF and acoustic incident waves;
- Medium to high sea state causes a lot of diffraction and random reflection of electromagnetic waves and it increases the ambient noise;
- The acoustic communication range and bandwidth are limited by the absorption coefficient, as function of local environmental conditions.

For both overwater and underwater regions, the transmission can be subjected to limited range, interruptions and loss of data because of frequency interferences and noise disturbances. Thus, it is very important to characterize the performance of communication systems in the real environment and to make tests in operative conditions so to identify limitations and to select/adapt protocols for improving performance and resilience. The subnetworks considered in the first year of SWARMs project have been tested at sea under a broad range of representative environmental conditions, during the Early Trials.

1. **Medium and High Frequency (MF and HF) acoustic subnetwork**: In this location, some different configurations of underwater networks have been analyzed according to the preliminary design definitions (star topology with mobile nodes and predefined path). Several tests were performed considering different protocols and routing algorithms, as well as adapting the transmit level in very shallow waters (5 m at the pier, up to 40 m in open water). In a final test it was possible to connect, on MF, the remote control station at the pier with the terminal node on a boat 1 km away in open water, reaching throughput values of 2 kbps. Regarding the HF modems, due to the preliminary configuration of the modem prototypes, the aim of the tests at pier were to test the performance of the acoustic transducers as function of distance and verify acoustic compatibility with other sensors (sonars, MF modems, thrusters, harbor noise) in rather shallow water (up to 5 m). Experimental results showed an effective throughput of around 66 and 16.5 kbps when distance was 10 and 50 m, respectively.

MF / HF: modems submerged at pier

2. **RF and Wi-Fi subnetwork**: These communication technologies and respective overwater subnetwork is based on state of the art components, which are commonly used, but specific conditions at sea can limit its performance and range. Particularly, parameters associated to spatial diversity, such as antennas distance, altitude over sea level and the stability of the platforms where they are installed, are fundamental in defining the system range and performance. Several different conditions were considered in the trials, such as: onshore CCS (Command and Control Station) antennas on top of a building and directly on a reef; antennas on board of boats, on mast between 1.5 - 4 m above sea level; sea state in the range 1 to 3 (at least) with strong wind; also various communication protocols, transmit power, polarization and also advanced techniques, e.g. spatial diversity and MIMO; a small rubber inflated boat simulating a buoy. In these trials, the achieved average throughput ranged between 2 - 7 Mbps, with latency values between 2.2 - 70 ms, and links range between 470 - 8700 m for Wi-Fi and RF, respectively, and according to the sea state that varied between 2 and 4.

RF and Wi-Fi: CCS onshore (top of building and reef), main boat and support boat

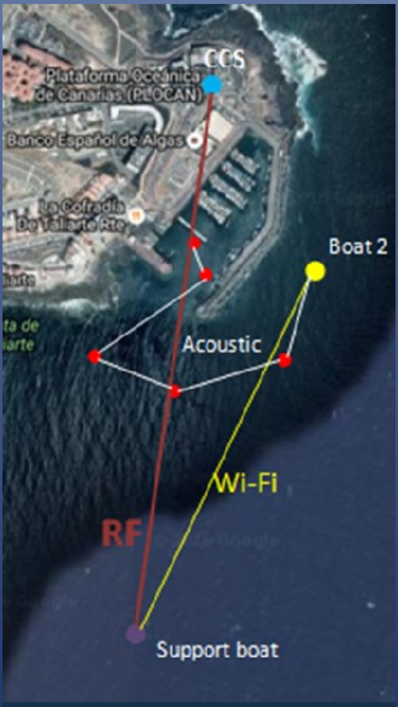
Early integration of the subnetworks

Following the achieved positive results regarding the considered subnetworks, a final test was planned and carried out integrating the RF, Wi-Fi and MF underwater subnetworks, demonstrating the capabilities of the designed and selected subsystems to transfer information from a remote control station onshore to an underwater node terminal at sea.

This experiment was repeated three times and it was part of the live demonstrations in SWARMs first Technical Review.

Moreover, in this demonstration it was possible to establish and keep a bidirectional communication link between the onshore CCS and the end point at the pier, where the communication full path was composed by:

- RF link from onshore CCS to a support boat;
- Wi-Fi link from the support boat to the main boat (Boat 2);
- Underwater acoustic subnetwork (MF) with 5 nodes, from the main boat to the pier.

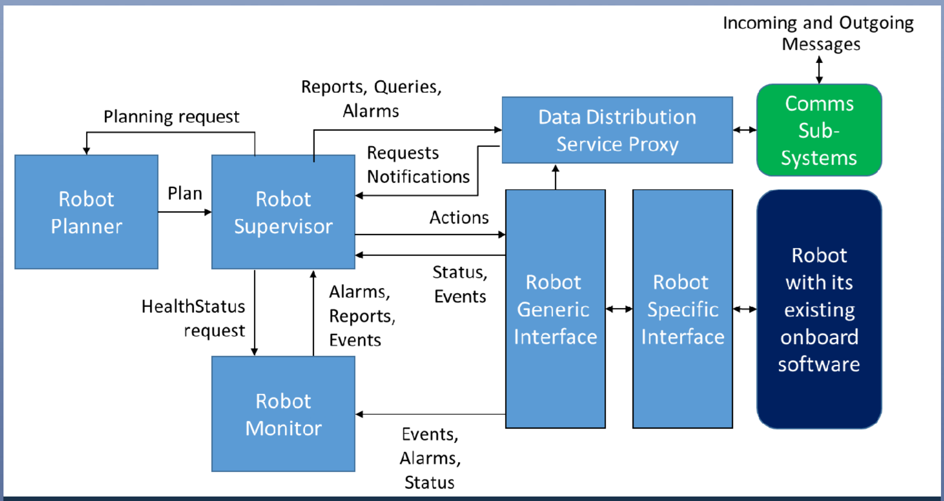


Early integration communication path

Robotic vehicles architecture

A generic software architecture is developed in the project and is being adapted to proprietary on-board software of the SWARMs heterogeneous robots. The main objectives are to allow each robot to receive high level mission tasks from the MMT (Mission Management Tool), to perform the requested tasks in a quite autonomous way including the cooperation with other vehicles, and to report to the MMT. Six software (SW) components (see figure below) have been specified:

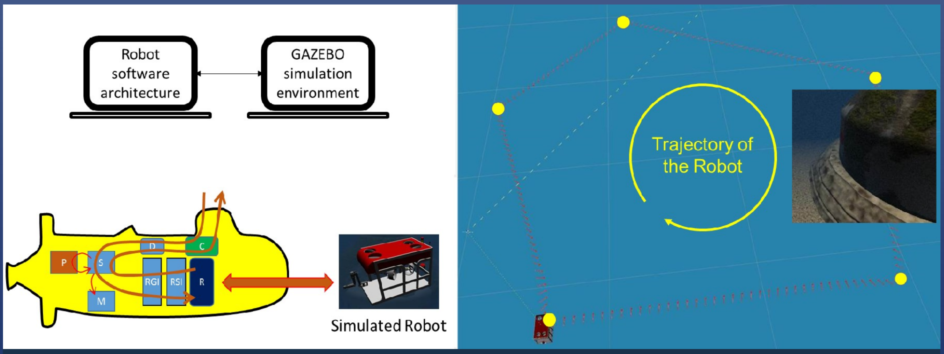
- The Robot Supervisor, central in the architecture, executes the planned actions, reacts to disruptive events and manages the robot configuration;
- The Robot Planner computes a detailed plan of actions from tasks received from the MMT and replans on disruptive events;
- The Robot Monitor monitors vehicle activities in order to detect faulty behaviors and generates health indicators;
- The Robot Generic Interface translates generic actions into generic commands and is the repository of data collected from the robot;
- The Robot Specific Interface translates generic commands into robot specific commands and collects data, events and faults from the robot;
- The Data Distribution Service Proxy interfaces with the external world (MMT and Middleware system) via the communication systems.


Incoming and Outgoing Messages
Comms Sub-Systems
Data Distribution Service Proxy
Reports, Queries, Alarms
Planning request
Requests Notifications
Robot Planner
Plan
Robot Supervisor
Actions
Status, Events
HealthStatus request
Alarms, Reports, Events
Robot Generic Interface
Robot Specific Interface
Robot with its existing onboard software
Robot Monitor
Events, Alarms, Status

Robot system integration architecture

The robot architecture has been connected to SWARMs simulator environment and data transfer was validated during the Early Trials:

- Reception of a mission vehicle task: inspect wind base turbine;
- Use of a pre-computed plan, i.e. a list of actions to move around the base of a wind turbine;
- Sending of actions to the simulated robot and receiving end of actions reports.



Simulation results at the robot level

Robot Operating System (ROS)

To ensure good level of genericity, the robots architecture has been implemented using the ROS framework: each light blue SW component represents a ROS node in the presented architecture.

Supervisor

State machines model the robot's expected behavior in nominal and degraded situations, and the plan execution function uses Simple Temporal Networks to manage temporal constraints.

Planner

Three types of planning problem must be solved on-board robots according to the different tasks of the mission: motion planning; area coverage; resources management. The problem and domain are described using standard Planning Domain Definition Language. Algorithms are under development to adapt to SWARMs challenges.

Monitor

Data from environment sensing and recognition, as well as robot internal check, are planned to be used to make diagnosis (now) and prognosis (future) for each generic vehicle action. Forecast algorithm relies on Boolean optimization (MaxSAT) and uses qualitative models and variables.

Next demonstration

For the first set of demonstrations in June 2017 at the Black Sea, three vehicles should on-board the SWARMs architecture and be part of a demonstration mission, which main goal is to monitor chemical pollution, namely H_2S.

Next demonstration participant robots

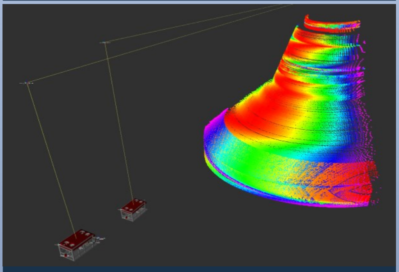
Vehicles simulator

One important part of SWARMs is dedicated in developing a set of functions to drastically simplify the tele-operation task in providing further autonomy to the vehicles, as well as the manipulation. In order to do so a set of simulation models are needed, which allow the model-based development and virtual testing of these functions before conducting expensive tests in the real world. In SWARMs, the chosen simulation environment is GAZEBO, which not only is able of simulating a swarm of robots, but also is the most popular 3D simulator within ROS ecosystem.

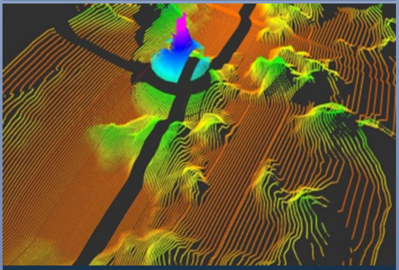
We now provide implemented models of vehicles, sensors, actuators and also manipulators. These models include the underwater vehicles used and provided by the project partners during the sea trials. Sensor models are typically generic with the possibility of parameterization according to a given sensor specification. The following sensors are currently included: inertial navigation system (INS), Doppler velocity log (DVL), underwater pressure, acoustic positioning (USBL, SSBL) and underwater camera (attenuation). In addition the user may define an amount of added measurement noise and drifting bias. Furthermore, the subsea environment was modelled and implemented. Besides fundamental hydrodynamic effects, models for wind turbines and terrain were developed and implemented.

Vehicle and manipulator control is currently under development. Basic controllers for the vehicles and manipulator are already available. The first missions were carried out with autonomous vehicles performing seabed mapping and inspection for bio-fouling on wind turbine foundations. Remotely operated vehicles could then be sent to these locations with the possibility to remove the detected bio-fouling with the manipulator arm. Animations of these missions, as well as demonstration of sensor outputs, the different vehicles and the environment, can be found in the SWARMs channel on YouTube. The simulator is released under the open source license Apache2.0 and is available at GitHub (uuv_simulator).

Modelled underwater vehicles



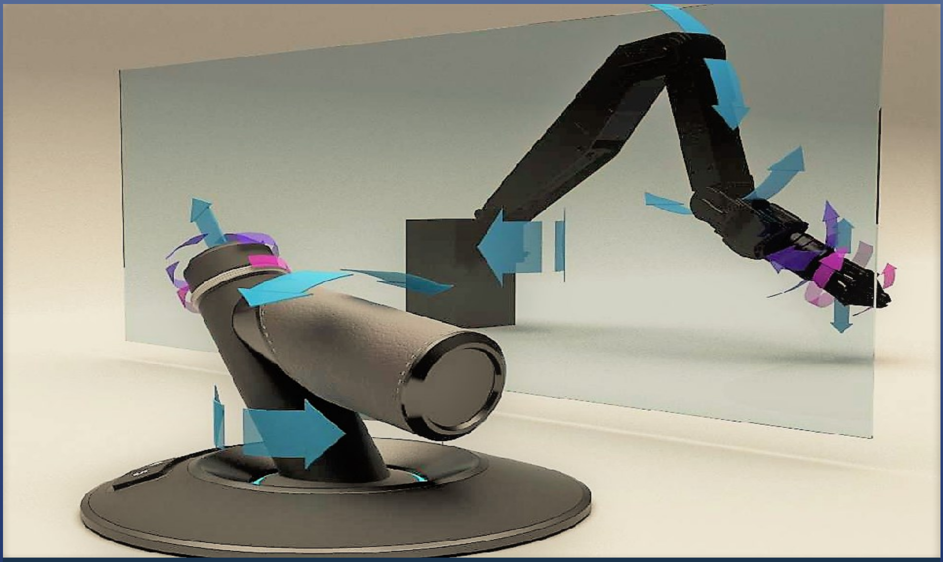
Scanning of wind turbine foundation



Simulation of seabed mapping

SWARMs intuitive input device

In SWARMs a device is needed to control a robotic arm of a ROV in a safe, reliable, time and cost efficient way. It should be able to reduce the training time of ROV operators. A first milestone for such intuitive input device was a conceptual design, represented by a 3D-printed presentation model. Technical requirements were derived after the problem definition. Existing solutions not only for ROV-operations but also for medicine, construction machinery, among others, have been analyzed accordingly. A problem definition was made to guide through the design phase of the input device, which should handle complex operations that may vary between scenarios, but also be intuitive and easy to operate. It should also be adaptable to different ROV types and manufacturers. Moreover, most users should feel comfortable with the ergonomics. Finally, the production of the device should be feasible in an efficient way, ensuring quality and usage of sustainable materials according to global ISO-standards. Combining the different elements discovered in this process allowed to create three solutions potentially fulfilling the requirements. From feedback of end users and systematic evaluation it has been decided to proceed with further development of the most promising concept, called Palm, currently also in a 3D printed model.



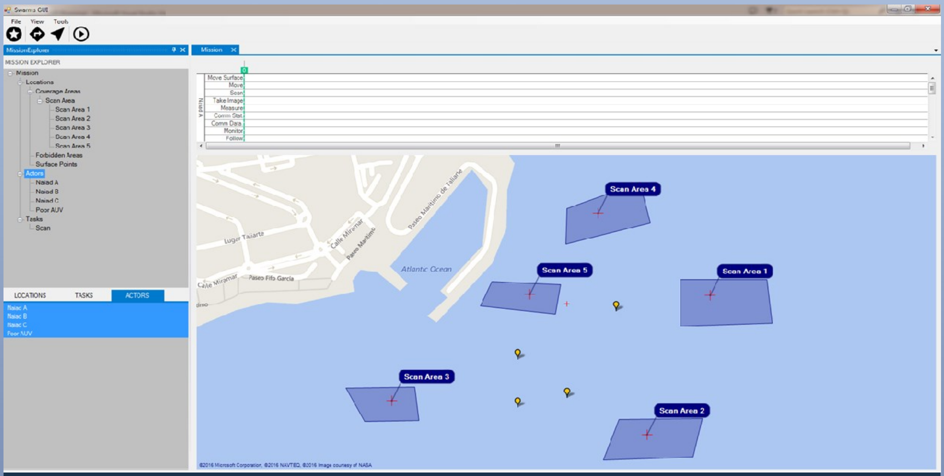
Concept of device before optimization

Final concept of the input device

Mission planning

High-level mission planning consists in providing the schedule and breakdown of tasks that need to be performed by a swarm of robotic vehicles for accomplishing a defined mission. On the other hand, low-level planning includes the definition of plans at vehicle level, i.e. the generation of waypoints, actions and equipment management commands. The following steps describe the planning of a seabed mapping mission in a high-level perspective.

1. **Mission definition**: The operator draws on a map the set of areas to be mapped, through the MMT graphical user interface (GUI). The system informs the operator of which vehicles are available and what are their configurations.

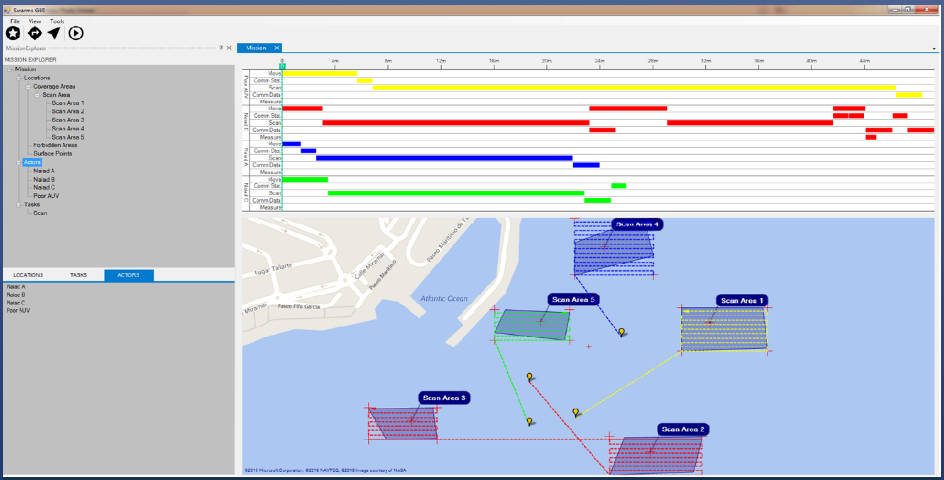


Mission management GUI

2. **Mission planning**: To optimize the whole mission and coordinate the swarm of vehicles, the system needs a planning model describing the available objects and their possible actions (or tasks). Given this model, algorithms called planners can compute the best sequence of actions to be performed by the vehicles, i.e. the plan. Within SWARMs, the mission planning subsystem hosts several planners, with different characteristics, or features, able to solve different models and computing a set of different plans.

3. **Task planning**: Among all the possible tasks, some are simple Boolean switch, e.g. "activate a sensor", while others can be complex problems, e.g. "move this object there". In order to efficiently compute the full mission planning, the planner must know, or estimate, the cost of a complex task.

4. **Gantt chart view of each vehicle plans**: The mission plan consists of a list of tasks assigned to each vehicle. Plans are shown on the map as paths, together with Gantt charts showing the tasks duration and execution order for each vehicle.



Gantt chart view in the MMT GUI

Planners features

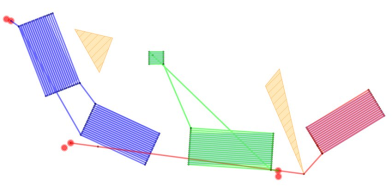
Planners / Features	Genetic planner	Heuristic planner	RKHS selection
Aggregated objectives	Y	N	N
Pareto	N	N	Y
Temporal	Y	Y	N
Optimal	N	Y	N
Anytime	Y	N	Y
Probabilistic planning	N	N	N
Preconditions	Y	Y	N
Modeling language	Y	Y	planned

Available mission planners

Planning algorithms

In the cost estimation of a complex task, the corresponding algorithm in case of problems that can be solved efficiently, may be the same that is embedded on board the vehicles. The corresponding task planning algorithms have been implemented:

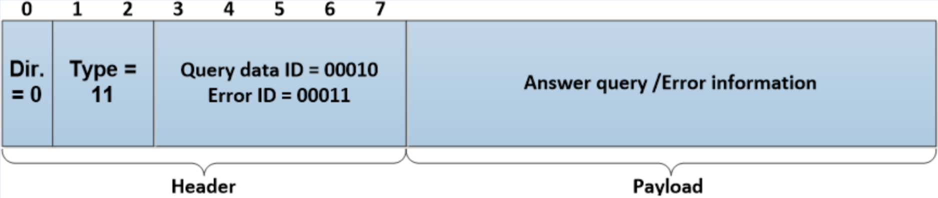
- Coverage path planning: how to cover a (rectangular) area with a sensor, while minimizing number of turns? Boustrophedon cellular decomposition was used.
- Single-Source Shortest Path planning: how to find all the shortest paths going from the current location to the corners of the covered areas and avoiding forbidden areas? Used visibility graphs and Dijkstra algorithm.



Example of trajectories for 3 vehicles

Interfaces with the middleware

In the latter part of SWARMs first year the first version of the interfaces connecting the vehicles with the semantic middleware (MW) have been designed, enabling SWARMs core functionalities. This design had to comply with the particularities of the underwater communication channel, i.e. low bandwidth that can drop entirely.



0 1 2 3 4 5 6 7

Dir. = 0

Type = 11

Query data ID = 00010
Error ID = 00011

Answer query /Error information

Header

Payload

SWARMs processing data unit (PDU) example

User interface

SWARMs user interface (UI) is centered on a three screen solution designed for controlling subsea vehicles in a swarm. It allows the user to link vehicles together to fulfill given tasks and to create larger operations consisting of several tasks. This system gives comprehensive view over a whole project and its operations, as well as documentation, both to professionals and newcomers. The three displays are divided into one map screen that shows the 2D and 3D map over work area, one timeline screen that shows tasks on a timeline, and one manager view where the operator can edit and view additional information regarding the vehicles and environment. These screens were developed with the help and feedback of actual effective users. The process started by understanding the overall situation, the work conditions of the user, the use cases themselves, and possible problems as well. Prototypes were tested together with the actual users and multiple iterations have been done. Early wireframe testing, without any colors or any final graphical elements involved, guides the attention to the correct functional features. This method ensures that the UI is built as intuitive as possible. In the latest part of the process, visual appearance was created and once more discussed with the end users. The SWARMs UI acceptance by users has been good. The final effective test of ROV/AUV monitoring functionalities will be done when back- and frontend designs are combined and set in action.

Conceptual illustration of SWARMs general user interface

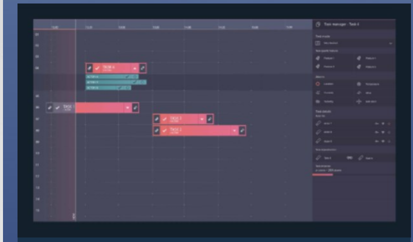
SWARMs PDUs

The interfacing in SWARMs needs to be rather light since it is not feasible to use typical interfaces over TCP/IP networks, such as REST, which are too complex and heavy. To avoid this, and after researching the state of the art, a communications interface has been designed compatible with the DDS (Data Distribution Service) middleware, using the RTPS (Real Time Publish Subscribe) communications stack. To transmit data in this format, messages are composed of series of bit-level data frames or PDUs (Processing Data Units) that codify complex messages in minimal space.

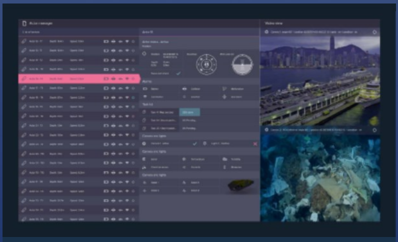
In the example above on the left, a concise 16 bit message is used to encode the response to a query, sent by a vehicle to the MW.

Currently, over twenty PDUs have been specified, and more are still being defined, in order to describe SWARMs complex system.

Map screen



Timeline screen



Manager screen

Give us your feedback: http://www.swarms.eu/contacts.html