PAPER

The European Project MORPH: Distributed UUV Systems for Multimodal, 3D Underwater Surveys

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ABSTRACT

The MORPH project (FP 7, 2012–2016) is aimed at developing efficient methods and tools to map the underwater environment in situations that are not easily addressed by current technology. Namely, the missions that are of interest are those that involve underwater surveying and marine habitat mapping of rugged terrain and structures with full 3D complexity, including vertical cliffs. Potential applications include the study of cold water coral reef communities, ecosystems from underwater canyons, pipeline and harbor monitoring, or the inspection of wind turbine foundations. The project introduced and advanced a novel concept of an underwater robotic system composed of a number of mobile robot modules (nodes), carrying complementary sensors for perception of the environment. Instead of being physically coupled, the modules are connected via communication links that allow a flow of essential information among them. Without rigid links, the so-called MORPH Supra-Vehicle can reconfigure itself and adapt according to the environment and mission goals, responding, for example, to the shape of the terrain, including vertical walls. The flexibility allows for more optimal positioning of each sensor, increased number of simultaneous viewpoints, and generally high-resolution data collection.

MORPH is aimed at providing a proof-of-concept demonstration of such capabilities, an effort that includes technological developments in many of the subfields of underwater technology. The main results are summarized and presented in this paper.
Keywords: cooperative control, distributed autonomy, underwater communication, image processing

Abbreviation List

AUV	autonomous underwater vehicles	PF	path following
CV	camera vehicle	PI	principal investigator
CWC	cold water corals	ROF	range-only formation
GCV	global navigation and communications vehicle	ROS	Robot Operation System
ICP	iterative closest point method	SSV	surface support vessel
LSV	local sonar vehicle	TDMA	time division multiple access
MBES	multibeam echosounder	USBL	ultra-short baseline (navigation)
MCL	mission control language	UUV	unmanned underwater vehicle
		VCS	version control system

Introduction

Exploration of the ocean is a challenging task, due to, in large part, adverse environmental conditions, lack of permanent infrastructure (as in terrestrial and aerial domains), and relative expense because of reduced market size. Autonomous underwater vehicles (AUVs) that work fully unsupervised are maturing and finding their way into practical applications. This is especially visible in hydrographic mapping tasks where the vehicle performs a survey of the seabed or water column by means of sonars and other sensors. These surveys provide a higher-resolution view of the underwater world than traditional methods but have some deficiencies, including the rate of acquisition and the lack of true vertical modeling. Another drawback is the fact that swath width of high-resolution sensors operating close to the bottom is quite narrow, in the range of 5 to 100 m. In order to expand the spatial diversity of sensors, one method is to employ a team of robots that flies in a formation and thus widens the practical swath width. This requires methods for coordinated motion control, distributed decision making, and intervehicle communications, all of which are prescient topics in the marine technology community. Projects like GREX (Kalwa et al., 2006) suggest solutions for applications of this kind, but due to missing adaptive abilities of the vehicles involved, preplanned formation flying was limited to more or less flat areas.

Often the geologically or biologically interesting areas coincide with areas with high diversity of relief; e.g., volcanic areas of the Mid-Atlantic Ridge, coldwater coral reefs or even manmade structures like foundations of wind turbines. In these areas with highly irregular surfaces, the existing methods (sidescan sonar, static formation) are limiting, and similarly, autonomous vehicles of today are not typically suitable for operating in these challenging unstructured environments. The autonomy problems are difficult in these situations, in particular, online mapping and sensing, real-time path planning with incomplete environment, and even self-navigation. Beyond the difficulty of these high-level autonomy problems in a space that is relatively empty (as is assumed frequently with AUV operations), there is real risk of vehicle damage or loss.

The current operating paradigm in the most challenging situations is to include human operators in the loop. This may be done with the traditional ROV operations or, as is becoming more popular, with hybrid solutions where the vehicle may have a tether with a direct command-and-control connection but is sufficiently autonomous to complete basic missions in the case of disconnection or may perform lightly monitored operations on autopilot. These solutions still only address a subset of the problem of marine vehicle operations in complex environments. The European Project MORPH proposes a solution to this problem. The paradigm is that a fleet of heterogeneous cooperative vehicles or self-driven sensors perform a multimodal survey of complex underwater structures. The spatial disparity provides the multiple viewpoints needed for both high-resolution surveys and obstacle detection and avoidance. The separation between nodes also allows different sensing mechanisms to operate closer to their specific optimum distance; e.g., sonar nodes are farther away from objects than camera nodes. The diversity in vehicles also allows for the combination of navigation and localization information; e.g., if nodes are sufficiently separated from interfering structures, they may have better navigation information than those close to such structures. More importantly, the distributed and physically disconnected nature allows for morphing, where the formation may adapt dynamically in real time to perceived changes in the environment that cannot be accounted for *a priori*.

The interdisciplinary questions that arise from this formulation are many and diverse: How should a distributed fleet of nodes navigate? What are the implied requirements for local or global navigation? How is such a fleet, with partial navigation information, to be controlled? How does the fleet morph in an effective and safe way? What decisions or feedback determine the morphing behavior? How does the morphing reactivity impact optimal sensor view and placement? Is the architecture hierarchical or distributed? Which nodes require which types of knowledge? How is effective mission planning performed? How is the mission monitored? How are the various data types assimilated into a cohesive and scientifically useful picture? These are the types of questions that MORPH investigates and, in many cases, demonstrates.

The scale of investment necessary in terms of both human resources and infrastructure is such that international joint cooperation has been crucial to progress. This is the reason that the 4-year-long project was cofunded by the FP 7 framework of the EC. The project started in February 2012 and found its final zenith in a series of sea trials in 2015. The project consortium was composed of nine partners. They shared the work under coordination of the German company Atlas Elektronik GmbH:

- CNR (Consiglio Nazionale delle Ricerche)–Istituto di studi sui sistemi intelligenti per l'automazione (Italy)
- Ifremer—Institut français de recherche pour l'exploitation de la mer (France)
- IMAR—Instituto do Mar, University of the Azores (Portugal)
- IST—Institute of Robotics of the Instituto Superior Técnico (Portugal)
- Jacobs University Bremen (Germany)
- CMRE—NATO STO Centre for Maritime Research and Experimentation (Italy)
- IUT—Ilmenau University of Technology (Germany)
- UDG—University of Girona (Spain)

In addition, Woods Hole Oceanographic Institution (USA) is involved in the project in the capacity of a scientific advisor.

Target Scenario and Requirements

As the "lighthouse scenario," the mapping of cold water corals (CWC) has been selected by the marine scientists in the team. CWCs, also referred to as deep-sea corals, are found in oceanic waters of all latitudes at depths ranging from around 40 to more than 1,000 m, with temperatures between 4°C and 12°C (Roberts et al., 2009). They are commonly found where current flow is accelerated, often around topographic peaks such as seamounts, mounds, ridges, and pinnacles as well as along continental margins and canyons. Some reef-forming species can create structures of considerable size that rival those of tropical coral reefs. Other species, such as gorgonians and antipatharians, may form dense stands that occupy large extensions of rocky bottoms, called coral gardens. These reef-like structures harbor a diverse community of fishes and other invertebrates and are biodiversity hot spots providing refuge and food to a suit of marine animals.

Studies on coral life history traits have shown that CWCs are the oldest live species on the planet—some species living up to a few thousands of years—and are extremely slow-growing (<1 mm/year). Their skeletons can hold paleoclimatic records that may help us reconstruct past changes in the deep-sea conditions and understand the potential impacts of current climate changes.

Because they are long-lived, slow-growing, and fragile, CWCs are particularly vulnerable to impacts from human activities such as bottom fisheries, hydrocarbon drilling, and seabed mining. In order to produce a detailed scientific analysis of the habitat characteristics and an understanding of factors regulating the CWC presence/abundance, health, and recovery following disturbance, there is the need to record following data:

- a high-resolution digital terrain map (resolution: 1–10 cm) of the cliffs, overhangs, and neighboring leveled areas;
- a high-resolution geo-referenced imagery dataset of the same area (1–5 mm/pixel);
- a high-resolution geo-referenced acoustic backscatter dataset of the same area;
- 3D reconstruction of the cliffs with draped imagery;
- geo-referenced near-bottom physical-chemical measurements (salinity, temperature, depth, light intensity [PAR radiation], pH, turbidity, current intensity);
- geo-referenced biological occurrences (i.e., coral colony positions and surface areas extracted automatically from imagery).

These requirements lead to the selection of nodes and equipment for the MORPH Supra-Vehicle. It is obvious that such results can be used in other applications such as pipeline or wind-farm monitoring, harbor inspection, and other kinds of industrial survey.

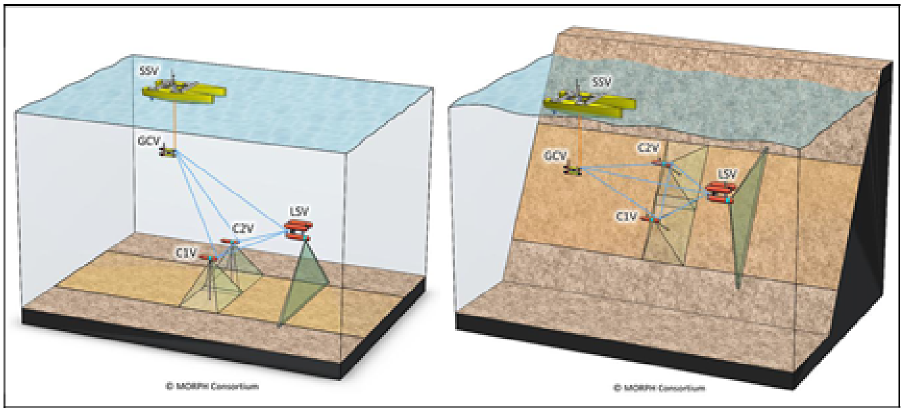
Introducing the MORPH Concept

The requirements above were developed with the knowledge that multibeam echosounder (MBES) and high-definition cameras were the payload sensors of choice for these applications. Ideally, cameras should have stereo capabilities that allow for 3D modeling of the environment. In order to achieve a good overlap between sonars and cameras, they need to be placed considering many factors, like multibeam swath width, camera field of view, illumination range, visibility, cost, and risk, to name a few. A possible configuration for the MORPH Supra-Vehicle that results from these considerations is depicted in Figure 1a. It shows an initial configuration of nodes flying over a flat bottom.

The core system for mapping the environment is made of one MBES onboard a local sonar vehicle (LSV) and two cameras onboard camera vehicles (C1V and C2V). Both the acoustic range and the swath width of MBESs are in general greater than the camera visibility and coverage, respectively. As such the LSV, flying at a higher altitude, can in fact cover the area that is exposed by two (or more) cameras. Having major navigation sensors on board, the LSV keeps a safe distance from the bottom and is responsible for leading the formation, detecting

FIGURE 1

An initial concept to operate a MORPH Supra-Vehicle in flat terrain and at a 60° slope.



and recognizing the environmental situation and triggering the formation adaptation. This detection is done both with a forward-looking scanning profiling sonar, but also a MBES used to estimate the relative angle of the survey surface. This angle is relayed to the following camera vehicles, which they use to modify their relative position setpoint in the formation. Figure 1b shows the MORPH Supra-Vehicle adapted to a MORPH-Roll-Angle of 60° in an idealized graphic.

The camera vehicles are the vehicles operating closest to the submerged structure and are assumed to have poor navigation. These vehicles actuate instead on relative localization information between the other vehicles in the fleet, using internode range measurements to modulate their position in the fleet, augmented by formation control cues from the LSV.

As the individual nodes do not roll, this clearly motivates the need of a "payload tilting mechanism" able to direct the MBES, cameras, lights, and other sensors to the wall being mapped. In the past, a few prototype vehicles, mostly ROVs, have already been equipped with a remotely controlled payload tilting mechanism. In MORPH, the approach is to install the mechanism in a number of heterogeneous vehicles and to operate them automatically in reaction to the shape of the terrain being inspected.

The mapping task requires a high accuracy in cooperative navigation of the nodes (a) in order to geo-reference the scientific data and (b) to bring the nodes very close to each other. The way of referencing the data with a global position is using GPS installed on a surface support vessel (SSV). In principle, this vehicle could be used to measure positions to the underwater systems using a standard ultra-short baseline system (USBL). But accuracy decreases significantly with depth and sea state. A solution to the problem is to "anchor" the MORPH Supra-Vehicle to a specific underwater node, far from the influence of sea waves, devoted to improving the navigation accuracy and relaying communications. The usage of this global navigation and communications vehicle (GCV) is instrumental in establishing the link between submerged nodes and the SSV, particularly in the case of significant overhanging cliffs. Additionally, the GCV provides absolute position measurements to the LSV for use in its internal navigation and uses those measurements itself to follow the LSV.

Overview of Major Contributions

To reach the ambitious goals of the project while minimizing risk, the work has been performed cooperatively by the partners. The following sections will summarize significant technical contributions of the project.

User Interface

One important key objective during the specification phase of MORPH was the definition of a clear road map for the development of the mission programming and mission control systems that are at the core of the MORPH project. This resulted in the specification of a list with basic cooperative behaviors, called primitives (e.g., following a vertical wall in a cooperative manner), which then needed to be realized by control algorithms. Also, these primitives formed the base for the important team-oriented mission planning.

A user interface for programming and visualization, denoted as MORPH console, has been created by IUT on the basis of QGIS (2016). This Geographic Information System allows using geo-referenced data as layer for mission planning. Such data may be any sea chart or even sonar data or results from previous missions. A plug-in has been implemented that allows the initiation of a goal-oriented mission of the MORPH system. Further additions have been made for mission monitoring and evaluation (Eckstein et al., 2013).

The final part needed for the complete mission planning process was a mission control language (MCL) to build the mission file that contains the mission plan and is spread to all vehicles before the mission execution begins. We decided to use the extensible markup language (XML) and a mission handler on the vehicle. It was a compromise between flexibility, security, and usability. We chose a dialect of XML, the State Cart XML (SCXML), as MCL. This SCXML was developed to describe a state machine. In Figure 2, an SCXML diagram is shown for a simple mission. The mission consists of the states Init, Morph, Travel, Survey, and End. Every state consists of substates and is linked to a next state via a transition. The transition condition is not shown in the figure. For example, if the "Init" completes successfully, the transition fires and the state machine jumps to the next state "Morph." If there is an error in the "Init" state, the transition to the "End" fires. It is possible to define parallel executed states. This is shown inside the travel state where some vehicles should do path following (PF) and some vehicles do range only formation (ROF).

Mission Control and Basic Software Design

The resulting mission plan must be understandable by all parts of the MORPH Supra-Vehicle. Therefore, a general mission plan handler, forming the core of the MOPRH software suite, has been created by IUT, which runs inside the individual nodes. The concept is described in detail in Eckstein et al. (2015). Besides the vehicle part of the software that already existed on each vehicle for single autonomous purposes, every other part is based on ROS (Robot Operating System, 2016). This decision simplified the process of connecting the different software parts. ROS as a middleware system offers a convenient way of distributing messages/data from one software component to other components. Every component is realized as a node in the ROS environment.

The software of a single MORPH vehicle consists of five important parts as shown in Figure 3. The first part is the already mentioned existing Vehicle Internal Control System, which remains running and is not changed for the MORPH project. To be able to connect every other software part of the vehicle, every partner provides a PC with a ROS system installed and a MORPH Vehicle Wrapper between the different software belonging to the Internal Control System on the one hand and the ROS part on the other hand. The Vehicle Wrapper has to connect the messages for speed, heading, and depth/altitude references and to translate the values for the vehicle systems and propagate back some system status information. The software parts/ROS nodes for communication and controllers are the same on every vehicle and are provided by different project partners.

The next important software part is made up of the Controllers. There are several of them for different tasks according to Figure 3. More details are given in Coordination and Adaptation. These controllers compute values for the speed, heading, depth reference for a given formation, path, and desired speed of formation. In order to achieve this, the controllers need some information from the vehicle like the GPS position or the depth, and the controllers need to send and receive information through a communication link. The communication link can be Wi-Fi when the vehicles are on the surface or acoustic communication for dived vehicles. The Communication block contains a ROS node called acomms (acoustic communication system). The acomms handles the data stream

FIGURE 2

State-chart XML-based mission plan.

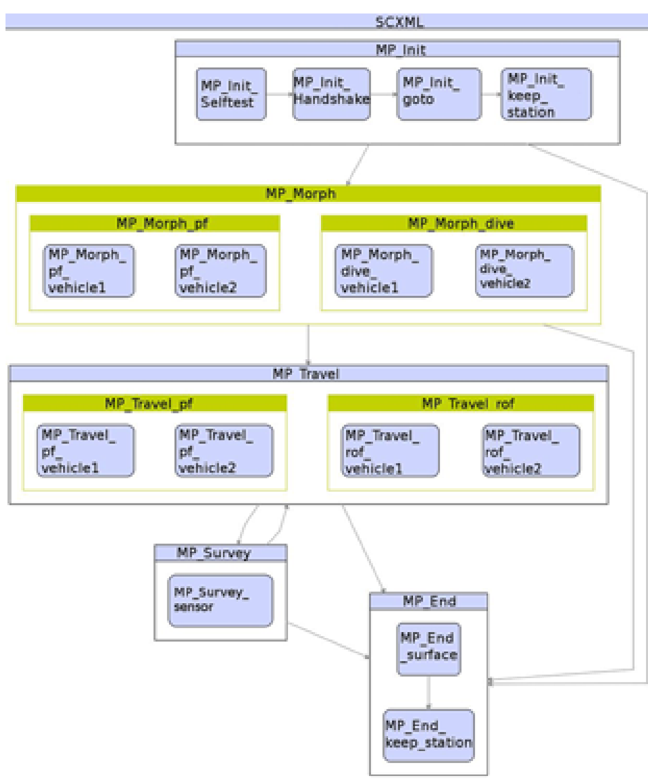
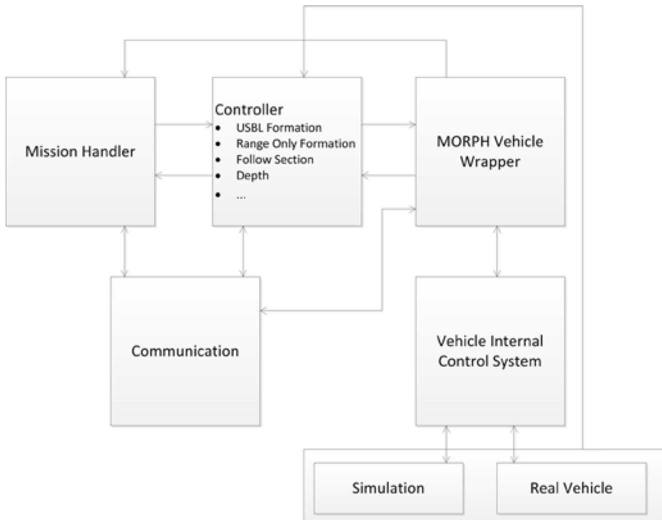


FIGURE 3

Software system on each participating vehicle.



from one vehicle to another and provides additional data like ranges between the acoustic modems and USBL angles for the controllers, which will further be discussed in The Communication Backbone.

The last software part is the so-called mission handler, which triggers and coordinates the different control algorithms to fulfil the goals given in the mission file. The handler is able to react on events that can be generated by other nodes; for example, by nodes processing the sensor data. Furthermore, the mission handler connects to the acomms in order to synchronize the mission state on all MORPH vehicles. In addition to that, the handler can receive command/events through Wi-Fi and forward the received data to other vehicles through the acomms, thus acting as a relay. In detail, the handler consists of three parts, the state machine, the MORPH part, and the mission control publisher.

The internal state machine is built up when reading the mission state chart XML, as described in the last section. The XML includes the states, all transitions between the states, and additional values; e.g., the formation for the "formation changing" primitive or the waypoints/arc for the "travel" primitive. All this information is stored in the state machine to be used by the other components of the Mission Handler. The other Mission Handler components can directly connect to the state machine to get the state and the values for the states.

The second part of the Mission Handler is the MORPH part. This part has knowledge of the defined MORPH primitives as described in the last section. Based on the states/primitives, the MORPH part decides what controller to start or stop and how to parameterize them. The MORPH part generates the standard messages to switch to the next state of the mission file.

The two first parts of the handler are not allowed to do potential blocking ROS interactions, as it is essential that they remain reactive during the mission. For that reason, the mission control publisher was introduced as a kind of communication wrapper and interface to the other software parts.

The mission control publisher broadcasts data directly through the Wi-Fi of the vehicle. These broadcasts distribute information between the vehicles and to the MORPH console. The Wi-Fi link from the MORPH console to a vehicle on the surface can be used to send waypoints, mission files, and events to the vehicle. The data for a mission file are not sent via broadcast. For that kind of data, a single connection from the MORPH console to the communication wrapper is opened, and the data are sent through the connection. In addition to that, the hash of the sent and received mission file is generated and compared. The mission file/waypoint is processed by the communication node, and other nodes are called if necessary.

The Communication Backbone

The MORPH concept and implementation relies heavily on a logical linking of physically disconnected nodes. This linking implies a direct communications system to relay coordination and control information and to forward command and control information between the operator topside and the deployed fleet. The communications system additionally provides the core relative localization mechanism for all internode formation control. This subsystem is a particularly strong dependency of many of the other driving technologies, and as such a critical component; the design is driven at directly addressing the MORPH requirements while trying to balance interoperability and expandability.

The underwater segment of the communications network relies on mature, commercial off-the-shelf (COTS) acoustic communications equipment to provide the low-level backbone for the communications stack. The software stack itself provides media access control (a simple time division multiple access [TDMA] implementation), a modem driver, and a highly configurable and customizable marshaling and demarshaling system for user data. Figure 4 shows the communications architecture for both the acoustic and wireless segments.

The used modems provide a synchronous messaging interface, which allows for relative localization solutions to be integrated into the network services. The relative localization capabilities include internode ranging via distributed long baseline (DLBL; Furfaro & Alves, 2014) and angular measurements from USBL-equipped vehicles. DLBL is a reformulation of the typical long baseline problem to use distributed assets to provide relative range information, without the requirement for moorings or synchronized clocks. DLBL is designed to run on top of any MAC, as the turnaround time is encoded in outgoing messages.

More detail regarding the communications system can be found in Furfaro and Alves (2015).

Coordination and Adaptation

Taking into account such constraints of underwater communication, a common control and navigation architecture for the nodes has been created under the leadership of IST.

Precise formation control is instrumental in ensuring that the MORPH system operates effectively. Given this, a hierarchical and distributed control approach is defined. The upper segment vehicles keep a formation using relative position measurements provided by an USBL system. However, due to the cost of specialized USBL hardware, the problem is constrained such that only one vehicle—the GCV—can measure its position relative to the others. Furthermore, specific geometries of the environment may block the communication link between the SSV and the LSV. As such, the formation should not rely on the SSV-LSV link, highlighting the importance of the GCV to relay information. As for the lower segment, no USBL is used; rather, the vehicles use range-only measurements, a virtue of the communications infrastructure, to keep the formation.

The LSV, out of necessity, carries a MBES and a profiler that allow it to reasonably sense the environment, specifically, allowing it to estimate the angle of the MORPH plane (see the MORPH Plane Detection section) or the slope of the local terrain. The vehicle runs a path-following algorithm on a planned trajectory (Maurya et al., 2009), which may be adapted online by a wall following mechanism (see the Wall Detection and Following section). The only information the LSV needs to receive continuously (i.e., every communication cycle) is its position in the earth-fixed frame.

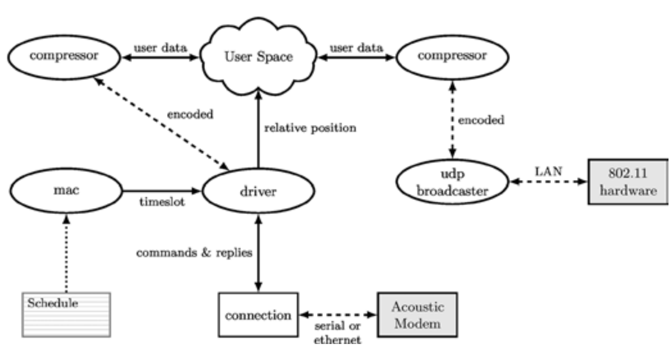
This information is obtained by the GCV, being equipped with an USBL system and measuring the relative distance and bearing to the LSV and the SSV. Simultaneously, it receives the global position of the SSV, which is determined by GPS measurements. The GCV then computes its own position and that of the LSV, forwarding the LSV position to it in the next communication cycle.

In terms of out-going information, the LSV broadcasts information about its motion, its depth, and the prescribed formation roll based on the identified wall slope. This information is used by all other nodes to compute virtual tracking targets and thus follow the leading LSV. While this is straightforward in the upper segment, where vehicles each know their global position, the lower segment (the camera nodes, CVs) has no access to relative position measurements. From the localization features of the communications system, the CVs are able to measure range to the LSV and GCV and, combining this with the tracking information broadcasted by the LSV, may estimate their relative position with respect to LSV. An advantage of this scheme is scalability, since the number of CVs can be increased without significant impact on the amount of information to be broadcast.

The final component of the formation control mechanism is a terrain compliance algorithm that manages the interaction between the prescribed

FIGURE 4

The communication architecture.



commands of the upper-layer formation control and safety requirements regarding altitude. This is a generalization of altitude control, as when the formation has been rolled out of the simple horizontal scenario, the actuation axis is not vertical but parallel to the MORPH plane and perpendicular to the survey surface.

Beyond the formation control aspects, there are methods for adapting the system behavior based on feedback of the mapping subsystems. These methods focus on specific degrees of freedom that are not constrained by the formation control or that may be locally adapted. These include (a) the overall formation speed (within bounds) and (b) a local adaptation of the camera roll angle with respect to the local variances of the terrain structure.

With respect to (a), the vision vehicles (CVs) analyze the information content or level of mappable detail of the camera images online and, if this quality measure falls below a set threshold, request a speed increase of the formation. Instead of a plain texture metric, it is also possible to analyze the geometric complexity of the terrain. Here, the intuition is that more complex terrain structures require a lower speed to be mapped accurately. The LSV as the leader of the formation receives the requests from both CVs and adjusts the global formation speed if both requests agree.

With respect to (b), the CVs use the estimate of the formation local plane received from the LSV as the initial estimate for their camera view angle, yet this angle may be suboptimal for the local view of the vehicle. Thus, the vision vehicles detect the dominant plane in the vehicle local point cloud and bias the sensor placement according to vehicle local irregularities.

In summary, the control mechanism for the MORPH fleet is a hierarchical architecture (both in terms of vehicle roles and subsystem composition) that is meant to address coordination problem in a sufficiently flexible manner to provide quality data outputs (Figure 5).

Online Environmental Perception

In the MORPH system, the LSV vehicle is operated at an altitude and distance far enough from the terrain to work safely. It uses MBES mounted on a pan-and-tilt unit (P&T). Tilting the sonar around the pitch axis of the vehicle gives a 3D point cloud in the front of the vehicle with a horizontal aperture of about 45°. The data are used in three different algorithms: (1) for determining the direction and slope of terrain, (2) for obstacle avoidance of the CV vehicles, and (3) for adapting online the mission plan based on the encountered terrain. These algorithms are briefly introduced in the following sections.

MORPH Plane Detection

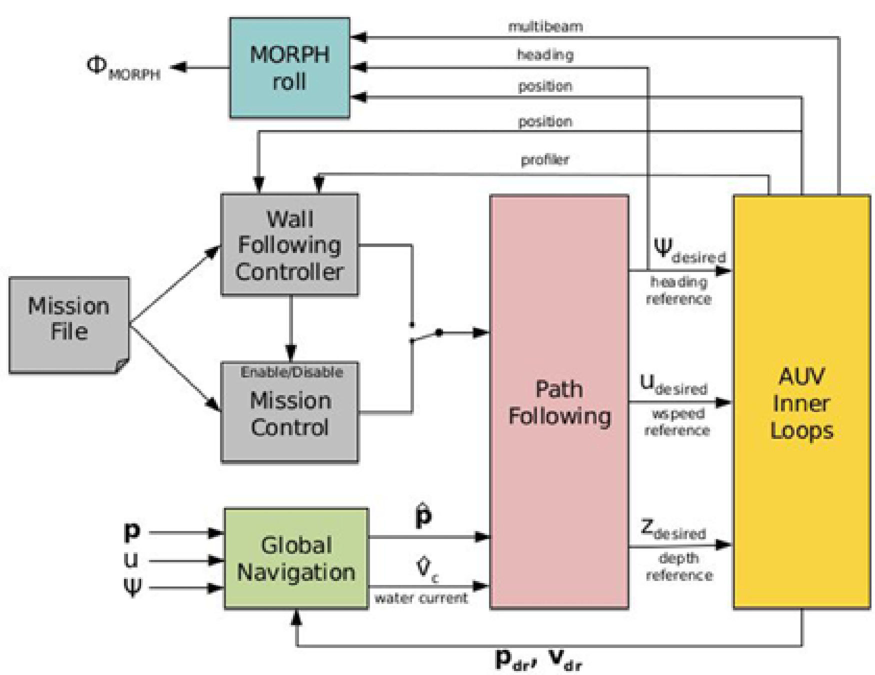
The MORPH plane is the plane orthogonal to the main terrain slope, whose angle with the vertical z axis (in north-east-down coordinate system) defines the tilt angle. This parameter defines the roll rotation angle for the formation and also for both CV's cameras and LSV's MBES. The MORPH plane is determined by the LSV online, combining each sonar profile with the AUV navigation to create a 3D point cloud. The MORPH plane is then broadcast to the fleet.

Wall Detection and Following

The missions planned offline by operators are not intended to be sufficiently resolved to deal with the fine-grained details of the to-be-surveyed underwater structure. In fact,

FIGURE 5

Block diagram of general architecture running in each of the follower vehicles.



operators likely do not understand the terrain sufficiently beforehand to plan such an exact mission. MORPH addresses this by incorporating an online planner, running on the LSV, whose goal is to guide the formation to follow the contour of walls whenever those are detected ahead by the MORPH plane detector described above.

To detect the wall, the LSV is equipped with a mechanical scanning sonar profiler (MSSP) to scan the horizontal *xy* plane in front of the vehicle. The scanned points are combined with the AUV navigation, generating a 2D scan which is used to extract line segments using the Split & Merge algorithm (Nguyen et al., 2005). Next, a parallel path to the detected wall is generated, obtaining a desired path to follow the wall contour (Figure 6). This desired path is fused with the one being followed by the mission handler. To do this, the desired path segments are tested for intersections against the current path section under execution. Whenever an intersection is found, the segment is joined with an arc of a preconfigured radius, which takes into account the limitations of the individual vehicles and the constraints of the formation. If the LSV is close to this arc, the section is accepted and the online mission is engaged. The mission continues, comparing the current section to the desired wall-parallel segments already detected. Intersections against the offline mission are also checked to determine when the fleet should rejoin the pre-planned mission.

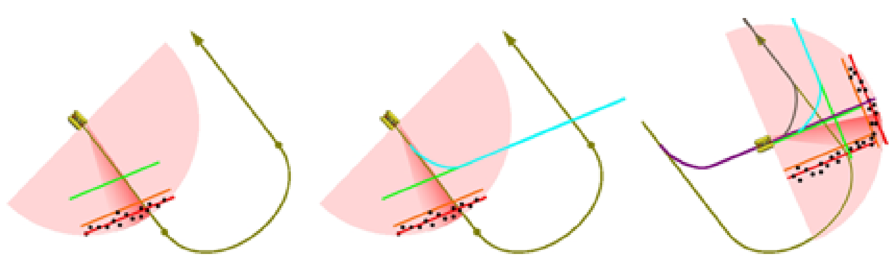
Obstacle Avoidance

While the LSV maintains a sufficient distance to the terrain to handle obstacles or changes in terrain geometry, the CVs must survey the structure in close proximity, while following the leader. This proximity leads to increased risk of collision, as the CV does not have the perception capabilities or view point of the LSV. Although this risk is partially alleviated by the terrain compliance module running on each CV, obstacles with sufficiently high relief may be difficult to avoid.

The problem is addressed by incrementally building a 3D map of the environment onboard the LSV from the sonar data using an OCTOMAP (Vallicrosa et al., 2014) representation. Simultaneously, the LSV has an estimate of the CV position (via the acoustic ranging). So, the net effect is that the LSV has sufficient information to detect any obstacles in the CV path and issue commands via the communications system that modify the CV positions in the formation. Swath is sufficient for obstacle avoidance. The MORPH formation and in particular the formation parameters of the CVs are sufficiently parameterized such that the LSV may issue geometry changes that affect the CV positions relative to the MORPH plane.

FIGURE 6

Wall detection and following, plan view: (a) The LSV approaches the wall following the mission plan (brown line), constructing a point cloud from the MSSP (black dots and red semicircle) and estimating the average slope (red lines) with the MBES, and determining a new terrain altitude for the formation at that specific depth (green line). (b) The LSV transmits this information to the fleet and begin to adapt the mission plan online to follow its own estimating of the wall geometry (cyan line), while also engaging a scanning sonar to detect the wall the side of the vehicle while the MBES continues to scan forward. (c) The LSV continues this process, evaluating the real wall geometry and average terrain slope against the mission plan, relaying course changes to the rest of the fleet, and maintaining distance with a scanning sonar. (Color versions of figures are available online at http://www.ingentaconnect.com/content/mts/mtsj/2016/00000050/00000004.)



Implementation, Development, and Validation History

This section describes the development and implementation approach, as well as the history of the project preceding the final demonstration.

Basic Research vs. Required Functionality

The development of MORPH into its final form has been a highly dynamic process. In particular, the project creates space for exploratory research tasks, while still requiring demonstrable technologies deployed in the water. As such, there are basically two groups of outputs: those of the "mainline" developments that are core components of the system that runs at seatrials and those that are optional components that are not required to be at a high level of maturity. Examples of those components are relative localization using light markers and cameras or optical communication systems for underwater node coupling. The workflow of the project, at a high level, has been to mature and stage those technologies and subsystems of the second exploratory group such that they are ready for inclusion into the mainline system while preserving and hardening the baseline technologies. This incremental approach can be analogously seen in the achievements of the sea trials.

The beginning of the project included extensive discussions, definition of specifications, feasibility studies, and basic research regarding the architecture and the process itself. These have been largely derived from the application scenarios that have been elaborated and defined in coordination with IMAR, the project's scientific enduser, such as those described in Target Scenario and Requirements. These products have been documented and served as guiding outlines for the definition of milestones.

Hardware and Software Adaptation

In the ideal case, the MORPH nodes may have been designed as standardized, small, and cheap self-driven sensor carriers. But the development of these was clearly beyond the scope of the project. Thus, the experimental realization of the MORPH concept relies on vehicles already owned by the project partners (Figure 7). The systems had very different properties that make them suitable for the different roles in the MORPH Supra-Vehicle.

SSV, equipped with GPS, underwater modem:

- Charlie (CNR)
- MEDUSA-S (IST)

LSV or GCV, equipped with MBES, scanning sonar, underwater modem; GCV also with USBL system:

- MEDUSA-D (IST)
- Girona 500 (UDG)
- SeaCat (ATLAS)

FIGURE 7

Vehicles that form the nodes of the MORPH Supra-Vehicle.

Camera vehicles (CxV), equipped with underwater modem, tiltable camera, distance sensor:

- SeaCat (ATLAS)
- AUVortex (IFREMER)
- Sparus II (UDG)

In order for each of the preexisting vehicles to become MORPH nodes, additional software and hardware components had to be installed. As exploited in the GREX project, the basic idea is to not change existing control software for the single autonomous vehicle but to implement uniform "wrapper" interfaces. The MORPH subsystems that must be ported to multiple vehicles are connected via an open source communication framework called ROS (Robot Operating System, www.ros.org), which provides a convenient and easy-to-implement interface for connecting multiple processes.

Simulation and In-water Validation

The development approach provides both for extensive simulation and in-water validation. Simulation typically serves to verify that the baseline configuration is correct, though exact parameters may be adjusted in real operational scenarios.

The consortium has relied heavily on the use of UWSim (2016) as a simulation environment for image- and sonar-heavy applications. UWSim is strongly linked to ROS, making the migration between simulated and real run scenarios very simple. While UWSim provides the sensor and environment feedback, the vehicle dynamics and control have been simulated using the real control software of the individual systems, which may or may not be developed in ROS. A MOPRH vehicle wrapper provides an interface between the vehicle software and the MORPH environment. The latter provides all functionality of the MORPH Supra-Vehicle including the acoustic communication network. To test the performance of the network, a simulator provided by the modem manufacturer has been added to the simulation framework.

The advantage of this architecture is that software which is used for the vehicle simulation connected to the simulated environment (UWSim) is identical to the software which runs on the vehicles at run-time. This allows that all software and configurations could have been tested in the simulation environment before they were deployed on a vehicle. This procedure proved to be best practice.

Trials History

An important aspect of the project is that the concepts have to be proven in real environmental conditions and not merely by simulations. Although simulations are a valuable tool and necessary part of the development cycle, the complexity of the real environment, in terms of sensor noise, hardware specifics, and model fidelity, always highlights problems that simulations cannot. As such the sea campaign of MORPH has been quite extensive, the general arc of which is described here.

The first multipartner experiment was held near Faial, in the Azorean archipelago (Portugal), in the summer of 2012. This experiment largely consisted of testing communications and DVL sensors in areas approximating the environment of the final demonstration scenario. The communications tests included early demonstrative results of the internode ranging mechanisms that would be refined later in the project (see The Communications Backbone). The selection of acoustic communications hardware (modems) was selected based on the results of this experiment.

One of the logical segmentations of the MORPH concept is that of the upper and lower segments of the MORPH Supra-Vehicle, which are principally treated unequally, each running different control algorithms. Thus, it was decided to split initial testing between these segments. Initial tests of the surface segment started early 2013 in La Spezia, Italy, by testing underwater communication between the AUV SeaCat and a surface craft while simultaneously testing the USBL hardware for the first time.

In the summer of the same year, the team headed to Toulon (France), and in the following spring to SantFeliu de Guíxols (Spain), to begin the first validation of the lower segment. These were the first of the "large" group experiments (>4 vehicles, >4 institutions, >20 researchers) and served as learning opportunities regarding the logistical and operational challenges that would be faced as the complexity increased.

The spring of 2014 saw the first advanced implementation of USBL formation control for the upper segment, first tested in a multipartner manner in Lisbon (Portugal). Several weeks later, the lower segment with the new formation parameterization features were tested, again in SantFeliu de Guíxols.

In September 2014, a large majority of the MORPH partners and assets traveled again to the demonstration scenario location in Faial, combining the lower and upper segments, demonstrating the systems efficacy in a flat survey demonstration. This flat survey used the SSV (Medusa S) to provide the gateway and absolute position fix to the GCV (Medusa D) and LSV (Girona 500), while the CVs (SeaCat and Sparus II) performed range-only formation control while simultaneously collecting optical imagery of the seafloor. This trial included operation of the Obstacle Avoidance algorithm operating on the LSV, giving guidance information to the following CVs. After the missions were complete, the data recovered from the fleet was fed into the processing pipeline, producing mosaics of the seafloor with simultaneous viewpoints from multiple vehicles. This trial, as a virtue of its location, also served to provide the group with logistic and operational experience in the final demonstration area.

After having achieved the flat terrain scenario, the next major milestone was to successfully adapt the MORPH Supra-Vehicle to vertical walls, a critical step of which was the detection of surfaces using scanning sonars. This was tested in the first half of 2015 in SantFeliu de Guíxols, first in March and then in June, first by introducing wall following, and then later formation adaptation (rolling).

Final Demonstration at Faial

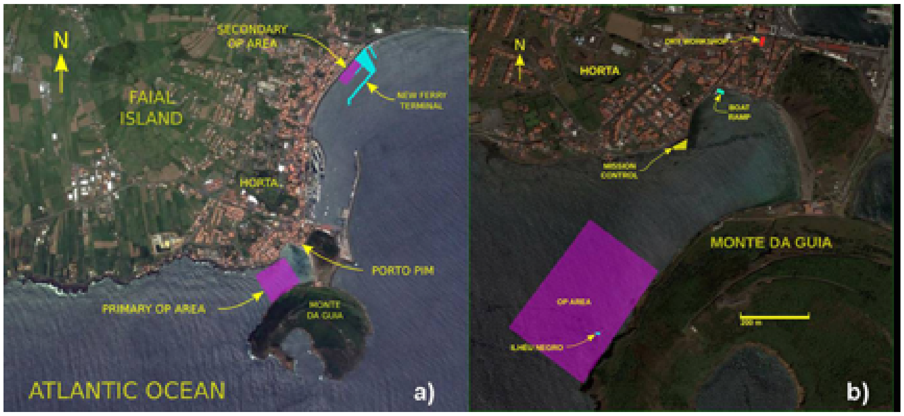
The ultimate goal of the project was to demonstrate the viability of the MORPH concept in the field to provide an effective solution to the complex task of 3D habitat mapping of underwater cliffs. The previous 3 years of research, development, and experimentation led up to the final demonstration in Faial in September 2015. In terms of resources alone, this included eight unmanned marine vehicle (one surface and seven underwater) and over 40 researchers hosted by IMAR.

The Missions

The operational area had been chosen as a trade-off between scientific relevance (as elaborated by IMAR and IFREMER to provide an area of interest, featuring an accessible underwater cliff) and accessibility in terms of operational depth and distance from a convenient shore base. The trials were conducted in two locations. Final configuration validations were performed

FIGURE 8

Operational areas (a) with respect to the city of Horta on Faial Island and (b) with respect to Monte da Guia, with IlhéuNegro marked in the lower right-hand corner.



inside the protection of the ferry harbor, while operational scenarios were performed at the underwater cliff of Ilhéu Negro within the Porto Pim Bay Area (Figure 8). Ilhéu Negro appears to be only a small rock perturbing the water surface at the entrance of the bay, though the major extent lies underwater and forms a vertical wall of about 50 m length and 10 to 20 m height. In terms of manual control and supervision, this was quite a challenge, as the distance between the shore base and the cliff measures about 580 m. IMAR/DOP provided a small support fleet for the vehicle handlers, one of which (RV *Águas Vivas*) was used as a mobile communications relay point.

The validating demonstrations consisted of a series of missions aimed at the execution of a video and sonar survey to map the underwater cliff and adjacent sea bottom. This required the dynamic adaptation of the MORPH formation to the unique, definitively nonflat bathymetry of the area. The work plan consisted of series of consecutive iterative steps, which aimed at reaching the full profile of a MORPH mission:

- offline planning using the GUI based on QGIS,
- online planning (wall detection and following),
- formation control,
- online planning using low-resolution data,
- reconfiguration for cliff mapping (morphing),
- resolution data acquisition,
- mission monitoring using the GUI.

At the beginning of the trials, reconnaissance missions were performed, including a conventional site survey using a multibeam sonar from the LSV alone. This data, along with imagery gathered by a flying quadcopter drone and a preexisting map, was overlaid in the GIS tool and gave the mission planners sufficient data to design initial missions.

In the next step, the flat bottom survey of the previous year was repeated. This took some time because of the fact that the main control algorithms had been changed in the year between. Subsequently the number of vehicles was increased until the full formation was successfully validated in the flat survey scenario. The next step was to approach the wall, where significantly more exciting environmental conditions were found. In particular, performance was degraded during several periods when acoustic performance was poor. It was found that there were certain "shadow zones" near the cliff face where acoustic communications suffered from very high error rates. This phenomenon was also transient, as it only happened for a period of a few hours during the 11 days of experimentation. The suspicion was that in particular sea states and prevailing winds, waves would crash over the top of the small exposed surface portion and formed deep bubble clouds on the leeward side where operations were occurring. When the "shadow zones" were present, the fleet geometry was rearranged in such a way that fewer vehicles had to pass through this area. During the trial, many of the other typical operational problems were encountered, such as hardware and sensor failures, limiting power budgets, and weather constraints.

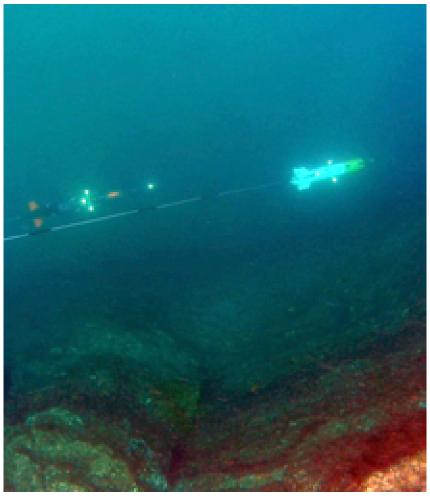
Given the difficulties of the trial, the end result was mostly successful, with the MORPH Supra-Vehicle mapping the cliff face and the surrounding areas, operating for some of the longest missions ever performed in the project (Figure 9).

Offline Data Processing

The data analysis phase was running in parallel with the in-water deployments, allowing researchers and operators to refine their methods with data analyzed from the previous days' missions. The data were used by UDG, JACOBS, and IFREMER to generate high-resolution 3D textured models of the surveyed areas. The availability of geo-referenced heterogeneous information provides the base material for the validation of the dedicated algorithms and analytical tools developed in the scope of the project, namely high-resolution 3D optical mapping, high-resolution 3D

FIGURE 9

The camera vehicles SeaCat and Sparus II perform wall following at Ilhéu Negro.



sonar mapping, and the combination of both, in the form of opto/acoustic registration.

The 3D optical mapping is achieved by exploiting data from both stereo and monocular camera images. The latter was based on the goal to create a generic mapping approach, which would be applicable not only to the MORPH project but to any input data meeting the same basic requirements. In this respect, monocular cameras are far more common in underwater surveys than stereo cameras. Nonetheless, the use of stereo imaging helps greatly to disambiguate the georeferenced reconstruction problem. Stereo cameras provide metric 3D reconstructions, thus enabling an easier merging of this 3D information with the navigation data stored.

The recovered 3D model of the area comes in a format that can be opened by most third-party visualization tools. However, note that simple tasks such as marking points or areas in the model are not trivial to achieve in the 3D case. No available off-the-shelf software is able to provide this type of interactivity with the model at a high level, so that a common user cannot realize those operations.

However, data labeling and area marking are simple tasks in 2D representations, as any image processing tool can be used to extract pixels and areas from them. Thus, it had been decided to build 2D geo-referenced and metric orthomosaics of the surveyed areas, which could be used for further marking and data extraction of the present biota. For example, the data gathered during the Horta trials fall into one principal plane containing the wall and into that of the flat area.

For 3D Sonardata, a bathymetry-based SLAM algorithm has been extended so it can work with full 3D sonar datasets. This algorithm is a pose-based underwater 3D SLAM that compounds swath profiles of the seafloor with dead reckoning localization to build surface patches (i.e., point clouds). Then, a probabilistic implementation of the iterative closest point (ICP) method is used to deal with the uncertainty of the robot pose as well as the measured points in a two-stage registration process including point-to-point and point-to-plane metrics. ICP is an algorithm employed to minimize the difference between two clouds of points. The point clouds of the surfaces to be registered are subsampled in order to decrease both the computational time and also the potential of falling into local minimums during the registration.

The MORPH formation takes advantage of two main types of mapping sensors: acoustic sensors such as MBESs are collected by the LSV, and the two CVs provide optical data. It is thus natural to attempt to fuse the properties of both sensor modalities into a single map in order to maximize the advantages of each medium. The fused map would benefit from the coarse, but large scale, resolution of the acoustic data, while the parts surveyed by the cameras would increase the resolution of the retrieved shape and additionally provide a better interpretation and analysis of the data by the texture information they can provide. In the scope of the project, two fusion approaches have been developed: (a) using the texture from the images as a means to colorize the acoustic surface and (b) increase the resolution of the acoustic mesh by using the higher-resolution optical data in the parts where they overlap. In the latter case, there are two meshes that have been properly geo-referenced. Thus, the problem naturally falls in the nonrigid registration methodology: we want the multibeam surface (the deformable) to mimic and morph toward the optical surface (the target). At each iteration of the method, an optimal deformation of the source vertices toward the target is computed, where this deformation is guided by a stiffness parameter restraining its movement. This step is repeated until convergence and then repeated for several decreasing stiffness parameters. An exemplary result is shown in Figure 10.

Scientific Results

Scientific objectives as part of the trials included the collection of physical-chemical data (e.g., temperature and conductivity) using sensors attached to three of the MORPH vehicles in the mission (Medusa Black, Sparus, and Girona 500) and collection and processing of biological data from 2D geo-referenced and metric orthomosaics of the surveyed areas. In addition, although not initially envisioned, JACOBS, ATLAS, and IMAR collaborated in the development of technology for the estimation of stingray population size (via visual

FIGURE 10

Results of the three methods of registration: optic (left), acoustic (center), and combination (right).

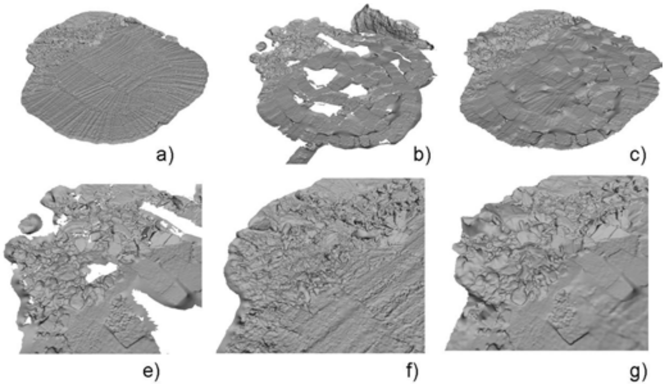
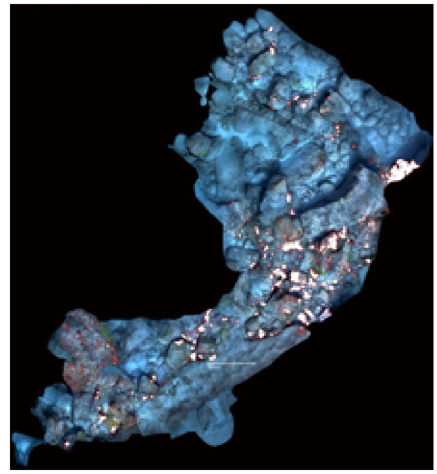


FIGURE 11

Segmentation result for *Asparagosis* sp. on a part of the rocky area, marked as white spots.



census) and fish size measurement *in situ* by stereo measurements in the Porto Pim Bay.

As explained above, the 3D mosaic has been converted into horizontal and vertical 2D orthomosaics in order to access the data in a more useful way. The horizontal mosaic resulted from multiple parallel and overlapping photo strips collected by the two camera vehicles during the horizontal segment of the complete MORPH mission; i.e., during the "zero"-shaped trajectories before the formation performed the MORPH roll into the wall, and after the MORPH roll, when the formation "morphed" again to the horizontal survey mode. This resulted in a large mosaic of 85 × 95 m, almost half this area, well characterized by large high-resolution 2D image, containing 813 m^2 of rocky habitat and approximately 2600 m^2 of sandy bottom.

Our analysis focused on the rocky habitat where invasive algae settle and grow, namely a green algae *Caulerpawebbiana* and the red algae *Asparagopsis* sp. We used the image analysis software ImageJ (http://imagej.nih.gov/ij/) to quantify the percentage of coverage of each of the two algae. Both algae have distinctive colors that allow a semiautomatic selection of the pixels associated with the specific color range for each species. When the adequate color threshold is fine-tuned, the "analyze particle" command returned the number of pixels highlighted, which can be converted into area according to image resolution, as well as percentage of coverage in respect to the entire image, including the black area and sandy bottom. To get to the percent rocky area covered, one has to determine and subtract the remaining nonrocky area using the same procedure.

The total estimated rocky area covered by *Caulerpawebbiana* was 8.3 m^2, corresponding to 0.39% of the available habitat within the sampled area. The estimated area covered by *Asparagopsis* sp. was substantially greater, with estimated 24.88 m^2 of rocky area covered, corresponding to 1.17% of the rocky habitat mapped (see Figure 11).

For the vertical wall, we followed the same procedure as described above. The "Ilhéu Negro" wall was mapped after the MORPH roll maneuver that allowed the transition from the horizontal to the vertical survey. The resulting images from the two CVs flying one above the other were used to generate a large high-resolution mosaic of over 40 m in length and 3.6 m in height (at the tallest section), with a total area reconstructed (rocky wall) of 603 m^2.

No *Asparagosis* sp. was detected during the detailed visual inspection of the high-resolution mosaic, which was also confirmed by divers on the site. The semiautomatic pixel detection allowed us to estimate the total *Caulerpawebbiana* covered area in 1.6 m^2, equivalent of 0.5% of the mapped wall. The estimation of algal coverage of the wall was more challenging than on the horizontal segment due to the fact that the wall is roughly oriented east to west, thus facing north. Due to this orientation, all surveys were done in very challenging lighting conditions, with the wall in the shade and cameras facing the sun. The *Caulerpawebbiana* colonies identified on the wall mosaic were confirmed on site by a diver. However, one colony was not accounted for since it was not contained inside the mosaic area.

Overall this method proved to be easy to use and demonstrated its great potential as an effective tool for detailed habitat mapping, including the early detection, monitoring, and support of eradication plans of invasive and exotic organisms such as *Caulerpawebbiana* and *Asparagopsis* sp. Detecting and mapping the presence and abundance of these aquatic organisms with conventional methods, usually by divers, remains quite challenging and very costly. Colony control/management or eradication efforts of aquatic invasive organisms would greatly benefit if a priory map of distribution and abundance would be available, allowing a realistic evaluation of success probability, realistic effort (man power and money) estimation, and the efficient allocation of resources. This tool can also be used to produce high-resolution habitat mapping and composition of reef habitats essential for marine spatial planning and resource management strategies.

This result closes effectively the loop that started by determining the requirements for the technical development by using the scientific scenario of mapping coldwater corals. Although these corals were not available at Ilhéu Negro, the potential of the MORPH system could be assessed.

Major Lessons Learned

The MORPH project is significant in its complexity, in terms of technology, people, and resources overall. Through the course of the project, though only 4 years in duration, there have been many notable lessons learned worth cataloguing. A few are discussed here.

Scientific

The overall consensus of the partners after the end of the project is that the paradigm of distributing sensors on multiple vehicles will continue to be an area of active research and serious commercial interest in the near future. The redundancy and flexibility of these disconnected systems reveal completely new application scenarios not envisioned before. Even when considering the simple idea of increased rate of data acquisition due to the increased number of sensors deployed, the advantage in terms of operational efficiency becomes quite clear. Projects like MORPH demonstrate some of the first semipractical applications.

Technical

From a technical perspective, there were many clear lessons to be gleaned from the project. Perhaps the most outstanding is the use of ROS as a framework for vehicle architectures. This middleware is very capable and extremely well suited to such a research project with many connected pieces where the interactions may change often in the development process.

Speaking also of software integration practices, it quickly became apparent that the use of version control systems (VCS) had to be a core component of every developer's workflow, even including mission configurations, network settings, and other small details. The project made use of git (http://git-scm.com/) as the unified VCS, which in hindsight was a good choice.

In terms of subsystem development, the role, importance, and limitations of simulation became clear in the early stages of the project. After a few difficult trials in the beginning, it was established that software was to be "checked out" before deployed in the water via simulation meetings that were arranged before every trial. Furthermore, the real world deployment of systems always introduces unforeseen consequences that require participants to be agile and flexible in developing solutions.

Management and Operations

Typically during trials, there are many people and assets involved, so the effective allocation of these resources is a nontrivial task. After the first few trials, the practice developed, largely organically, to establish local 'scientist in charge' roles, which was assigned to capable individuals to manage and guide the work for the day, maintaining the focus and direction of the group. This person usually worked in coordination with the local trial hosts, which tended to be the PI of the host institution. Operational trial days would have routine morning and evening briefings, which would bring the entire group up to speed on goals and achievements and served as resource staging opportunities.

Cultural

Clearly, the greatest strength of this project and the sole reason for the level of success is the engagement of the individuals. The achievements are a direct outcome of the dedication, flexibility, expertise, and initiative of the team members. One of the most critical features of the teams was the maintenance of clear and open communications channels. Key developers of different subsystems were frequently in direct contact with each other, running simulations online, or even supporting remote tests.

Summary and Future Plans

This paper presents the final state of research of the European Project MORPH as achieved by January of 2016. The significant, high-level achievements have been described, including

- an environment for software development that supports collaborative work, which includes extensive simulation capabilities;
- a mission syntax that allows effective control of mission process while taking into account time and event driven triggers;
- a common software based on the ROS framework allowing to convert any AUV into a MORPH node, with the addition of a simple unified interface;
- a reliable acoustic underwater network as a basis for communication and relative navigation;
- formation control by a mixture of methods that take into account the properties of the roles of the nodes and their sensor capabilities;
- coarse online mapping as basis for environmental adaptation, which includes
  - relative slope sensing for optimal formation and sensor placement,
  - automatic contour following and path-replanning,
  - distributed obstacle avoidance,
  - advanced methods for offline scientific data mapping and visualization;
- development of scientific requirements and final demonstration of scientific utility.

There are many other achievements not described here that contribute to the efficacy of the system. Some more information can be found on the MORPH project homepage http://www.morph-project.eu and in many publications as cited in the text.

Having finished the project, the collaboration among partners will persist. There will be upcoming networking events that can be found on the web like "Breaking the Surface," organized by the University of Zagreb, or the yearly "EMRA" Conference at various places. Some of the technology will be used in further European projects like WiMUST, where former MORPH partners contribute. As a general push, the ROS framework seems to be widely adopted by the marine robotic research community.

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