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ISME Research Trends: Marine Robotics for Emergencies at Sea

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***Abstract*—One of the main recent research trends of the Italian Interuniversity Research Center on Integrated Systems for Marine Environment (ISME) is the use of marine cooperative teams of autonomous robots within the fields of security, prevention and management of emergencies at sea. Such fields are of worldwide interest for obvious reasons, but they have recently gained relevance in the current historical moment, especially in the Mediterranean sea. Within such a dramatic context, the use of robots could certainly provide helpful for the execution of patrolling and detection, identification and classification of interesting elements, such as people to be saved or oil leaks, as well as the successive execution of the intervention/rescue strategy. This paper presents the Key Enabling Technologies as well as some Key Research Areas that are being currently investigated by ISME toward the ambitious objective of employing robotic solutions for the management of emergencies at sea.**

I. Introduction

The Interuniversity Research Center on Integrated Systems for the Marine Environment (ISME, Italy) is working since more than a decade in marine robotics, with special focus on unmanned systems, from the theoretical, experimental and technological transfer point of views.

For example, ISME and Selex-ES, Italy, one of the leading players for providing large systems aimed at security and surveillance, have collaborated on different projects focusing on the critical infrastructure protection problem. In particular, within a joint research project called Swarm Management Unit (SMU) [1], which has the ultimate goal of developing a complete solution for managing and supervising a team of Unmanned Surface Vehicles (USVs) operating in a (semi-)autonomous manner within a civilian harbour, ISME's Genova node has developed a real time motion planner based on the three layered architecture presented in [2], [3], [4], and methodologies for the interception of suspect vessels [5], [6].

Still regarding security applications, the Cassino node has developed several methodologies for the patrolling problem [7], [8], while the operative unit of University of Pisa has worked on evaluating the performances of the harbour protection developing a GIS-based simulator able to assess the level of underwater security in civilian harbour installations [9], [10].

One of the main recent research trends of ISME is the use, within a System of Systems (SoS) point of view, of marine cooperative teams of autonomous robots within the fields of security, prevention and management of emergencies at sea.

Such fields are of worldwide interest for obvious reasons, but they have recently gained relevance in the current historical moment. This is especially true within the Mediterranean sea, mainly due to the illegal migration flows which are increasingly taking place there, with associated tremendously high costs in terms of disaster occurrences and loss of human lives.

In this dramatic context, the European (and even more the Italian) scientific community is compelled to contribute with research activities to address this issue, in the attempt, on the one hand to improve the effectiveness of the emergency control and management means, and on the other hand to reduce the risks and the efforts of the personnel directly involved in the actuation of rescue operations at sea.

Toward this end, the use of automated operative solutions can certainly provide high benefits. Indeed, within the EU Horizon 2020 program, different calls have been already scheduled to develop technologies for security applications, in which for those at sea the employment of unmanned autonomous systems is specifically foreseen.

Within such a dramatic context, the use of robots could certainly provide helpful for the execution of the following important tasks:

- patrolling and detection of interesting elements (features such as people to be saved, or oil leaks);
- identification/classification of the elements through multi-robot consensus;
- execution of the intervention/rescue strategy.

Adopting a SoS approach leads to model the problem of sea emergencies as the interaction of agents belonging to two broad macro systems (MS), namely one devoted to execute patrolling/survey missions and one to intervention ones. A MS is a set of heterogeneous robots with certain capabilities to carry out specific missions, for which they require the availability of certain Key Enabling Technologies (KET), as well as the methodologies from some Key Research Areas (KRA).

In particular, the above mentioned tasks require the cooperation of robots belonging to the two broad MS. These include:

- Autonomous Underwater Vehicles (AUVs), for searching and tracking underwater features and their eventual recovery;
- Unmanned Aerial Vehicles (UAVs), to have a comprehensive view of the disaster area, and be able to cover long distances quickly;
- Autonomous Surface Vehicles (ASVs), which can carry high loads and act as a gateway and support base for the two other kind of vehicles.

For the above reasons, the current research trends at ISME intend to address some of the KETs that are needed to envisage a future applicability of automated solutions within the above explained emergency scenarios, as well as to continue the studies in some of the KRAs where further methodological advancements are still needed.

Finally, ISME cooperates, since many years, with the National Center for Naval Studies and Experimentations (CSSN) of the Italian Navy at La Spezia, now also within the framework of the recently established joint research lab on Heterogeneous Marine Autonomous Systems (SEALAB). This cooperation allows ISME to have full access to all experimental and logistic facilities of CSSN, including the free access to their own reserved wide marine area for experimental field trials. Furthermore, this cooperation allows a fast transfer of the research activities to the personnel directly involved in the emergency situations, as well as having precious feedback during the developmental stages.

This paper is organized as follows: Section II presents a brief review of past and current marine projects where ISME is involved, which have some common background with the required KETs and KRAs needed for tackling emergencies at sea; Section III explains the current ISME research framework on the subject; finally Section IV draws some concluding remarks.

II. Related ISME Research Projects

Cooperative teams of heterogeneous autonomous vehicles must be able to carry out patrolling/survey activities in integrated forms, for detecting and then classifying interesting features, which might later be the subject of a specific intervention. The patrolling/survey MS must rely on some topics at large, such as cooperative patrolling and related algorithms; communication infrastructures, mechanisms and protocols; distributed image/sensor based features detection and classification; and their related enabling technologies, some of which still need to be adequately developed.

The literature relevant to each topic and its enabling technologies is very wide. Nevertheless, at least some recently concluded and/or still running EU Framework Programme 7 (FP7), EU Horizon 2020 program (H2020) as well as Italian National projects (PRIN) can be quoted here, to give a rough idea of the current state of the involved main topics and enabling technologies (where at least a member of ISME has been, or still is, an active research participant), namely:

- FP7 CO3AUVs (Cooperative cognitive control for AUVs, 2009-2012) [11], in which the basis for patrolling activities to be performed by homogeneous teams of AUVs has been established; advanced cooperative patrolling algorithms have been devised and validated, even if on a scaled proof-of-concept experimental basis.
- FP7 UAN (Underwater Acoustic Networks, 2008-2011) [12], where the fundamentals for underwater acoustic communication networks, including AUVs as mobile nodes, have been established; basic communication protocols have been developed and experimentally tested on scaled field trials [13].
- PRIN ROAD (Robotics for assisted diving, 2014-2017) [14], where cooperation between surface and underwater vehicles is exploited to supervise in a semi-automatic way the activities performed by teams of divers.
- H2020 WiMUST (Widely scalable Mobile Underwater Sonar Technology 2015-2018) [15], where precise cooperative formation control of a team of substantially homogeneous AUVs is tackled, for geotechnical prospection purposes.

As instead regards the intervention MS, different sophisticated and possibly cooperative intervention actions have been considered in the perspective of a possible employment in a near future, at least as support to manned rescue operations. These include, for example, aerial transportation of lightweight emergency items, underwater grasping and transportation to surface of objects to be recovered from the seabed, or surface caging of floating items (e.g. small drifting boats, possibly with people on-board, etc.).

Again, we provide an idea of the state of the art by quoting some recent EU funded projects and national PRIN projects (all with contributions from members of ISME) on the involved topics; namely:

- FP7 TRIDENT (Marine robots and dexterous manipulation enabling autonomous underwater multipurposes intervention missions, 2010-2013) [16], where free-floating manipulation has been developed and proved in sea trials [17], [18], [19].
- PRIN MARIS (Marine robotics for intervention, 2013-2016) [20], where cooperative underwater manipulation is being studied [21].
- H2020 DEXROV (Dexterous ROV: effective dexterous ROV operations in presence of communication latencies, 2015-2018) [22], where the supervisory control of ROVs is tackled.
- H2020 ROBUST (Robotic subsea exploration technologies, 2016-2019), where deep-mining exploration will be studied.

The results from the above projects represent the chronological sequence of the most recent development steps performed on the general topics of marine patrolling and intervention that are currently being exploited and further improved to the scopes of managing emergency situations at sea.

III. Research Framework

In this section we discuss the research framework. In particular, different KRAs have been individuated:

- Surface patrolling via cooperative ASV-UAV teams;
- Medium depths underwater patrolling and/or seafloor survey via cooperative ASV-AUV teams;
- Higher depths underwater seafloor surveys via cooperative AUV team;
- Consensus for classification of multi-agent detected features;
- Feature-based reasoning, planning and intervention at classified features;

In the remainder, we shall discuss each of these KRAs in a dedicated subsection.

A. The Patrolling/Survey Macro System

1) Surface Teams: A team of ASVs cooperatively executing patrolling activities on the sea surface can be considered as the starting system for incrementally construct the considered overall MS. Each ASV can be assumed characterized by adequate maneuverability capabilities and endowed with the necessary sensory package (electro-optical devices, surface radar or sonars, etc.), which is a reasonable assumption considering the current technology status. These requirements enable each ASV for the execution of monitoring activities within its own corresponding surface visibility area. Furthermore, each vehicle can absolutely localize itself via GPS, while a wireless MANET (Mobile ad hoc NETwork) should be established among the vehicles, thereby enabling a suitable and robust (with respect to weather conditions) connectivity among teammates. The design and validation of such MANET is one of the KETs being currently developed by ISME.

With respect to the adoption of surface patrolling policies, it is noteworthy that relevant expertise is already available within ISME, ranging from simple deterministic policies based on area partition, to the more promising ones based on distributed coverage and data exchange between neighbouring agents [23], [24]. Such techniques are currently being further investigated and tested/validated.

2) Integration of Aerial Agents: The operability of the surface team can be improved in case few of the ASVs are allowed to launch an associated UAV exhibiting flying autonomy. Such an UAV can be employed as a suitable extension of the ASV visibility area or, whenever more UAVs are in flight, as a complementary aerial patrolling team.

Once an UAV is flying, a direct radio link with the associated ASV allows for the real-time data exchange between the two, possibly including the transfer of the acquired raw images to the mother ASV itself. This direct link allows the UAVs to implement patrolling policies similar to those applied to the ASV team, without the need of extending the MANET to such nodes. However, this requires the connectivity between each UAV and its mother ASV to be maintained.

For these reasons, studies addressing the development of such a type of heterogeneous teams integration are being tackled by ISME.

Finally, regarding the critical problem of an UAV flying and landing on a moving ASV in harsh conditions the following issues are being analysed:

- Development of robust or even adaptive to the identifiable disturbances (waves and wind) cooperative UAV-ASV control algorithms capable of managing the final quasi-docking phase of landing;
- Similar to the previous point, robust UAV control algorithms in case of flying in presence of harsh wind disturbances, including indications about the aeronautical characteristics (for instance number, allocation power of the thrusters) an UAV should exhibit for allowing the implementation of the needed disturbance-rejection control algorithms;
- Design of mechatronic systems capable of guaranteeing the reliable mooring and firm binding of the UAV after the final phase of quasi-docking. Such systems should also include automatic mechanisms for the UAV battery charging or swapping.

The above points constitute KETs that are investigated and being developed by ISME.

3) Integration of Underwater Agents: Underwater patrolling at medium depths (e.g. within 50-100 m) can be efficiently implemented via small lightweight, high-maneuverability T-AUVs (tethered AUV), each one umbilically connected, for fast real-time data exchange as well as for power supply, with an associated ASV with respect to which the T-AUV can self localize via an endowed Ultra Short Base Line (USBL) device.

The problem of underwater patrolling has similar objectives to its aerial counterpart and it shares a fair part of methodologies. Furthermore, the above ASV/T-AUV system shares some analogy with the ASV/UAV one. However, there are differences mainly in the kind of adopted sensors (sonars are usually preferred to imaging cameras in the underwater domain) and for time and covered distances. Another important difference with the aerial case lies in the fact that the patrolling activities will be mainly done by the submerged T-AUVs and that the presence of the umbilical cable constrains the T-AUV/ASV couple to cooperatively navigate in order to avoid dangerous cable entanglements. At the same time different T-AUV/ASVs should stay sufficiently far apart, to avoid the same problem with different umbilicals. The development of solutions facing these aspects is another area where ISME is deeply engaged.

Notwithstanding the above considerations, the two kind of patrolling activities are being studied taking into account their differences but also trying to share results and having a unified approach as much as possible.

4) Seafloor Surveys: Seafloor surveys are foreseen at generally higher depths (e.g. more than 100 m), with the aim of detecting and classifying features, objects, or more generally items, which are considered to be important, for instance, for the analysis of a post-disaster situation (e.g. sunk vessels, boats or even aircrafts, tracking a chemical leak plume), for the evaluation of dangerous situations from a geological/geophysical point of view, etc. For such cases, even if the related operations are generally not always characterized by urgency, the use of AUV teams is proposed as means for increased efficiency and reliability. Three fundamental structural problems, very specific for the underwater environment and common to any conceivable approach to cooperative seafloor mapping, must be considered, namely:

- the very low bandwidth allowed by acoustic communications among all teammates;
- the impossibility of acoustically transferring (for instance to a surface supporting vehicle) the acquired seafloor images within a reasonable time;
- the self localization of each teammate and the position knowledge of at least its neighbours.

In this context, the hereafter proposed approach is currently being analysed and tested/validated, which mimics the one explained for the aerial vehicles: each AUV localizes itself with its assigned ASV through USBL means. The ASVs exchange the AUVs positions through the aerial MANET and in this way they now have the knowledge of all the AUVs positions. Finally, each ASV sends to its corresponding AUVs the position of the neighboring ones, through the acoustic link. This framework will allow the AUVs to employ patrolling techniques similar to the ones outlined for their aerial equivalents, although in slower forms. The development of an underwater acoustic communication framework (an UW-MANET), complementing the aerial one, constitutes another core research area of ISME, and the existing acoustic limitations are being carefully taken into account, to the aim of achieving the best allowed performance [25], [26], [27].

To save costs, instead of equipping every vehicle with USBL, a LBL (Long Base Line) system could be used as a mean to localize the underwater vehicles. To this regard, ISME has already investigated the impacts of calibration errors of LBL system in the localization estimate [28], [29].

Finally, with respect to the transfer of the acquired seafloor images to the surface, rather than waiting until the end of the survey, the AUVs can exploit the presence of the T-AUV for the data transfer. This can be done by getting close to the T-AUV and hovering very close to it and resort to blue-light optical communication (megabits/s of reliable bandwidth within such short distances) for transferring the acquired stream of images [30]. This will allow to save time, as the AUVs will not need to emerge to the surface and will enable a more timely supervision of the survey by the command and control center. The visible light communication is another KET that is currently investigated by ISME.

5) Feature Detection and Reliable Classification: When a distant feature is detected by a patrolling ASV or a related UAV, its classification may still result uncertain (a floating human body or an inanimate object?). This may consequently require the execution of approach manoeuvres, by part of the detecting ASV/UAV, in order to reduce the uncertainties and to achieve a final classification. Moreover the same feature might even be detected by different agents, which should therefore reach a consensus about what they have detected. Techniques for achieving a consensus in presence of different images have been recently proposed, starting from a preliminary pre-processing performed on the acquired images. In our case, by mainly referring to features detected by UAVs, we will consequently have different images separately pre-processed on board the related ASVs. The consensus algorithms for final classification will be executed on one of these ASVs. The herein outlined aspects constitute another important part of ISME research activities that are carried together with University of Parma RIMLab group.

B. The Intervention Macro System

Following the classification and geo-referentiation of what we have generally termed as a feature, typically a corresponding intervention must be exerted regarding the feature itself. It is here assumed that the decisions about intervention are taken by a (manned) tactical command and control center (C2) ground or ship located, toward which the information relevant to the detected features is made converging by one of the ASV in the field acting as a C2 transmission gateway.

Although it can be foreseen that most of the interventions, in particular those at surface and especially in harsh weather conditions, will still continue to be actuated via manned means, it is deemed that at least the hereafter listed ones can be considered as worthy candidate to be automated, with as highest as possible level of autonomy, to be at least employed as support to manned interventions:

- Surface transportation of emergency items (e.g. life jackets, inflatable rafts, etc.);
- Surface caging and towing of items (e.g. small drifting boats, possibly with people on-board, etc.);
- Aerial transportation, possibly in cooperative forms, still of emergency items (typically of small volume/weight) [31];
- Underwater grasping and transportation to surface of items from the seabed [18], possibly in cooperative forms (in case of large volume/weight objects) [32];

The first two tasks are carried out in collaboration with the CNR-ISSIA Genova node.

IV. Conclusions

This paper has presented the latest ISME research trends on the use of marine cooperative teams of autonomous robots within the fields of security, prevention and management of emergencies at sea. Examples of such emergencies include the disaster of the British Petroleum oil rig in the Gulf of Mexico (2010), where automated systems have been used to track the underwater oil plume, or the Fukushima disaster (2011). For cases closer to the Italian border, we recall the Haven disaster near Genova (1991) and the continuous stream of boats from North Africa, with the frequent occurrences of ships sinking and their high toll of human lives.

Within such a dramatic context, the use of robots could certainly be helpful for the execution of the following fundamental tasks: patrolling and detection of interesting elements; identification/classification of the elements through multi-robot consensus; execution of the intervention/rescue strategy.

The execution of the above tasks requires deeper methodological investigations in different Key Research Areas which have been discussed in this paper:

- Surface patrolling via cooperative ASV-UAV teams;
- Medium depths underwater patrolling and/or seafloor survey via cooperative ASV-AUV teams;
- Higher depths underwater seafloor surveys via cooperative AUV team;
- Consensus for classification of multi-agent detected features;
- Feature-based reasoning, planning and intervention at classified features.

Finally, ISME is investigating a number of issues that needs to be solved in terms of some Key Enabling Technologies, including: the realization of Aerial and underwater MANET; UAV-ASV cooperative control for UAV takeoff and landing; mechatronics for UAV-ASV final docking and recharging on ASV; and underwater optical communications.

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