Security e operazioni subacquee: i sistemi autoorganizzanti

Lo studio presentato in questo articolo è il risultato di un progetto finalizzato alla messa a punto e realizzazione di una nuova tecnologia marina, adatta all'uso in missioni di ricerca e salvataggio di naufraghi, protezione civile e navi militari contro attacchi terroristici, nonché alla ricerca e identificazione di congegni esplosivi pericolosi. La fusione del concetto di swarm intelligence con quello di reti di comunicazione multihop è la risposta al coordinamento durante operazioni subacquee complesse. La supervisione umana in tempo reale (in-the-loop) può essere valorizzata migliorando le prestazioni di comunicazione e ridefinendo il concetto di teleoperazione. L'elevata efficienza che la comunicazione può raggiungere rende il sistema particolarmente adatto per l'esplorazione di vaste aree in tempi brevi, come in operazioni di salvataggio in alto mare quando i tempi di sopravvivenza dei naufraghi possono ridursi a pochissimi minuti. Un prototipo swarm è attualmente in fase di collaudo.

Underwater security: Self organising systems

The study presented in this paper is the result of a project aimed at the development and realization of a novel marine technology, suitable for missions like search and rescue of people at sea, protection of civil and military ships against terroristic attacks, and search and identification of dangerous explosive devices. The fusion of the concepts of swarm intelligence and multihop communication networks is the answer to the coordination in complex underwater tasks. Human in-the-loop supervision can be exploited increasing communication performances and redefining the teleoperation concept. The high efficiency that communication can reach makes the system especially suitable in exploring large areas in short times, as in deep-water rescue operations, when the survival time of people lost at sea can be limited to very few minutes. A swarm prototype is currently under testing.

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Introduction

Life is a continuous challenge to man's adaptation to the environment. The new paradigms created by the human science for artificial beings must face the same problems.
Along with this development philosophy and looking at the sea as one of the most promising environments in terms of humankind's economic expansion, ENEA

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tried to improve the current capabilities offered by the present AUV (Advanced Underwater Systems) technology relevant to mobility, perception and communications. We chose to follow the potential offered by the multi robot systems along with the philosophy of the swarms proposed by Reynolds [1], with substantial innovations on the paradigms of collective intelligence and sensing.
One of the needs is to efficiently control a high number of vessels with a central control console, coping also with the need to integrate and summarize the data coming from many different swarm elements. Another target is the system adaptivity to environmental modifications affecting communication, whether inter-individual or with the supervisor. These aspects are both related to the physical communication channel and to the geometrical distribution of the multi robot system.
The research we are carrying out at ENEA, supported by a large end-user consensus and by national projects like Harness aims at overcoming both limitations by means of an intelligent spatial distribution of transmission nodes. The project is aimed at the design of a swarm endowed with an internal intelligent architecture characterized by a close synergy between communication and geometrical/dynamical control of the swarm itself.
This paper is devoted to the role that underwater robotic teams can play in ensuring security conditions to critical infrastructures, ports, and ships. An analysis is also carried out on the high critical tasks of search and rescue following shipwrecks. Within the Harness project, funded by IIT and internally co-funded, ENEA developed a first 4-vessel swarm currently under testing.

Security needs in marine areas

Large water surfaces of Oceans and Seas have played a critical role in all the human history.
Currently the economic activities involving seas are ranging from communications (i.e., underwater cables joining continents), to large and heavy transportation, energy (offshore platforms, oil and gas terminals), food fish and farming, tourism, military actions.
Practically each one of these activities is potentially subjected to natural, military or asymmetric threats and the most critical targets, some of them involving the security of whole nations, are often not adequately protected.
Special attention is requested by end users to the protection of ships, critical infrastructures, ports, etc.. against passive (i.e., mines) and active threats (underwater attacks by scuba divers), and to the rescue of people fallen at sea. What makes robotic swarms especially useful in security actions is their capability to fill and control large volumes of water by means of a network of cooperating sensors, and their capability to move in the most interesting zones, increasing density where it is needed the most. They are also easily transportable and deployable in a small or large number of vessels.
Recent studies have been carried out by end users on applications relevant to the protection of large critical infrastructures, customised according to the features and the peculiar characteristics of our system and playing the role of second protection level. In these schemes the first level is accomplished by fixed multiphysics antennas (surface radar, underwater sonar, optical sensors, etc.) that gives a continuum picture of the surrounding environment, with a relatively high possibility of false alarms.
When an alarm is detected a swarm or part of it can be sent to intercept the alarm source(s) and to check its real threatening potential. The interception swarm must be relatively wide, fast and continuously connected to the Command and Control Room to obtain the precise position of the threats detected by the antennas of surveillance sensing system.
Currently ENEA has been called to participate in national projects for ensuring the security of sensitive infrastructures by means of this technology.

Ports surveillance

This application comes from the need to avoid intruders from taking advantage of the large traffic of a port to carry out threatening actions using explosive, radioactive materials or biological attacks.
Usually actions of this kind are monitored by surface

sensors, like surface radars and optical surveillance devices, yet such systems have a limited alarm capability when the threats are brought by divers. Several scenarios have been studied for asymmetrical attacks: some of them refer to the transportation of divers to a distance suitable to reach the target by underwater swimming. Acoustical barriers can offer adequate protection, but their main drawback is their need for frequent maintenance to ensure their effectiveness. This is a considerable cost and they cannot be managed in a flexible way since deployment and withdrawal operations are also expensive and time consuming.

The use of mobile surveillance nodes can represent an effective alternative to these systems. They offer the possibility to be easily brought into operation only when there is an actual need, in very short times and without any external evidence of the operation. The alert system can be operated using different approaches, ranging from acoustical barriers (passive or active) to visual alarms and magnetic alerts.

In addition to their security functions, these tools have also been considered by large European ports (Le Havre, Rotterdam, Marseille) as a practical device to explore the conditions of the vessel of large ships, within their loading and unloading operation, without having to recover them into a hangar or to realize fixed sensing equipment in every dock.

The preliminary analysis has also characterized the fixed equipment as an expensive approach, considering the maintenance needs and the fact that only a limited number of docks could be exploited for this use (almost half of the docks in a large port are usually under maintenance conditions and, therefore, not suitable for ship docking).

Requests for detection barriers and rescue operations

The capability to search and detect bodies at sea is a surprisingly important request. Some years ago our group has been advised about the importance of such a capability during a preliminary presentation of the ENEA's underwater swarm project later named Harness.

The interest was in the threat represented by the possibility for silent diving intruders to overcome all the ships' electronic defenses thanks to the modern scuba equipment. Acoustical barriers cannot be deployed in all the cases, especially when ships are anchored outside the ports and, on the other hand, the classical sonar equipment cannot be effective in most cases since the human body, having a density very close to that of water, often absorbs the sonar beams and suitable suits can further decrease the tiny echoes. The capability to deploy an acoustical network of protecting mobile nodes, based on the lacking of transmitted sonar pulses rather than on their reflection, seemed therefore greatly estimated by the end user.

For an analysis of some possible approaches to the sensor coverage the theme has been widely treated and we can refer to the works of Liu [2] and Barr [3].

The concept of a safety equipment deployable in case of needs turned out to be much wider than in the mentioned case and urged our group to study the problem more deeply.

The chance of survival for people fallen at sea is quite low, especially in cold climates, and decreases quickly if the body is not immediately recovered. When shipwrecked people start losing their forces and are no longer able to continuously sustain themselves on the surface, the detection possibilities become quickly worst and worst.

A mobile swarm like the one discussed for ships' protection can become a powerful tool also for the rescue of people lost at sea. The combination of two resources of such a system, the capability of efficiently apply a volumetric detection, and the capability to keep trace of the explored volumes can be considered an important advantage in many cases. Also mine fields can be efficiently detected and then removed with the appropriate tools by means of this detection method. Despite the fact that they are intrinsically more detectable by sonar ships, there are modern mines protected by means of phonoabsorbent surfaces.

General considerations on the ENEA's project

The underwater environment is strongly variable from

a communication point of view, depending on salinity, turbidity, presence of dissolved substances that change the color and transparency in different optical bands.
Therefore communications can take place with greater or lower speed in the optical or acoustical channels, with different delays, attenuations, angular distributions of the radiated power. A multi-body system, can react to these modifications modifying both the parameters of the transmission "equipment" and the physical dispersion/geometry of the system itself. If the mission of the system demands for a greater dispersion to maximise the volume to be explored, the communication bandpass could be reduced and the main stream of the information could be switched from the optical to the acoustical mode. Natural examples are in the following Figures 1 and 2, representing a couple of typical situations.
Common mode behaviors often generate peculiar geometrical shapes as an answer to survival challenges. These behaviors are the result of learning processes that are partially carried out during the life of the swarm [12] and partially carried out during the evolution of the species through a genetic selection process. Some reference shapes have been defined as a reply to the needs of selected applications in Figures 3, 4 and 5. The global control architecture is built around three basic elements: the supervisor goals, the inter-nodal communications, the priorities of each single individual (typically collision avoidance). The behavior and the swarm configuration will change

FIGURE 1 Adaptation of a bird swarm to environmental need (food hunting)

FIGURE 2 Cylinder shape obtained by the internal rules of a swarm, usually as a reaction to a threat by a hunter

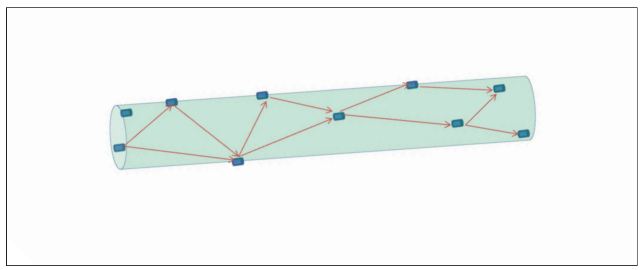

FIGURE 3 The "pipe": when the communication is the main objective of the geometrical shape to transport data on long distances at high data rates

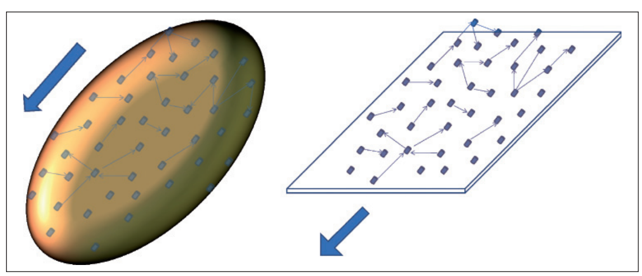

FIGURE 4 - 5 The "plane", especially suitable to carry out fast and parallel survey operations of the basements. Especially aimed at allowing a high rate exchange of information among the nodes. "Ellipse" is a quite typical shape used in fish schools, typically aimed at giving the most impressive "footprint" to possible predators, but it is also the result of the dynamical processes of arrangement of the schools themselves

depending on the assigned tasks, the survival risk associated to the operation of each robot and the risk relevant to the loss of connection of each vessel with the multi-body system as a whole.
Previous studies to address the formation control and coordination can be found in [4] and in the basic work of Khatib [5].

Research challenges and first steps

The concept of a multi-body system that behaves, to some extent, as a single entity is in line with the approach followed by nature's evolution. Societies, Swarms, Colonies down to the case of an individual, seen as an association of specialized cells, are all different forms of multi-body systems where the specific nature of the association is determined by the optimal answer to environmental conditions.
The following basic challenges are addressed:

a) Overcoming the problem of low data transmission bandpass inside marine water;
b) Drastically improving the monitoring capability for tasks requested in sea coastal areas (pollution and biological controls, intrusion surveillance, rescue operations);
c) Getting an easy and fast supervised control by a human operator, at a high-level decision capability.
d) Optimizing the system behavior in different environments to improve its robustness and reliability;

In the following, the facility realized for the preliminary tests is shown (Fig. 6).
The final vessel has been designed in the ENEA's labs after a long time spent to optimize all the economically relevant components. Our final objective was to achieve a vessel, big enough to transport a minimum amount of sensoriality and to have a reasonable autonomy, but as cheap as possible to put together a realistic swarm.
From the assembly drawing, after further optimizations on the electronics, we realized the first prototype of VENUS (see Fig. 7).
Currently 4 VENUS vessel prototypes have been realized, the single vessel testing is in progress (Fig. 8) and the first swarming tests are expected to be

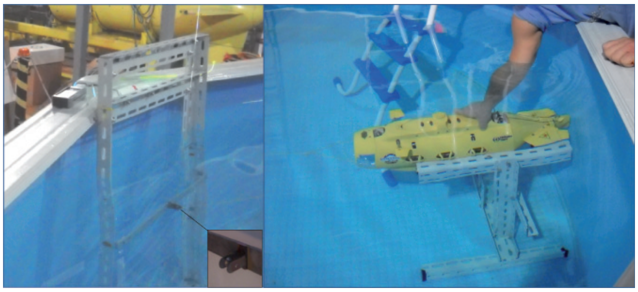

FIGURE 6 Commercial low-cost platform in the ENEA's testing pool facility

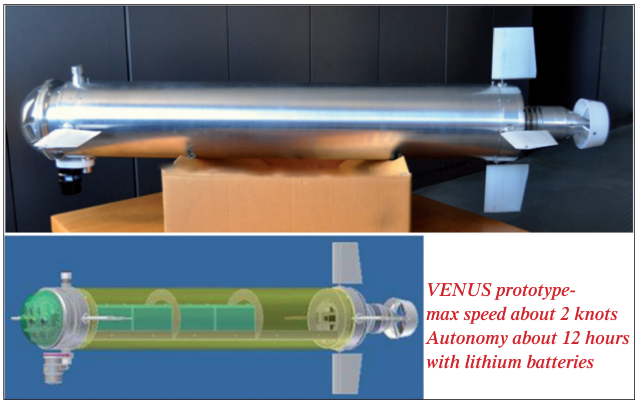

FIGURE 7 First prototype of VENUS

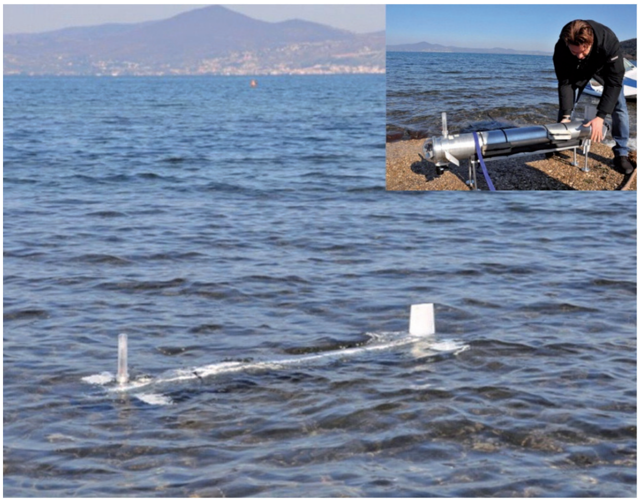

FIGURE 8 Venus testing at Bracciano's lake

performed by the end of the current year. Incoming projects should make the realization of large functional swarms possible.
The algorithmic work carried out so far has led to the following results in the simulation test-bed:
- to maintain short distances among all the swarm members;
- to change the swarm geometry with the specific task, flat distribution to explore wide surfaces,
- to simplify the remote control interaction, treating the whole system as a single composite body.

Four technology areas are envisaged as key elements of the architecture: Communication, Control, Localisation, Teleoperation.

Communication

Most of the intelligent swarm functions are based on performances of the communication channel.
The underwater environment strongly limits the practical signals that can be exploited [9]. We considered the following different categories:
a) acoustical active signals,
b) acoustical passive signals,
c) electromagnetic (optical) active signals,
d) electromagnetic (optical) passive signals,
e) electromagnetic active signals (only for surface communication).
In the following, some issues of this critical subject will be discussed.
The underwater swarm is a wireless network of mobile nodes able to cope with different needs, depending on the physical arrangement of the node geometry. We envisaged at the least:
a. the need for a fast data transmission rate on relatively long distances (High Speed Transmission); a pipe geometry, small distances and slow movements are the conditions to adopt sensitive protocols like PSK and QAM for video streaming;
b. the need to increase the swarm internal data exchange (High Swarm Bandpass) to allow processing like the fusion of data from the sensors of many vessels on the same target;
c. the need to maintain a disperse swarm configuration to accomplish wide area monitoring tasks (Wide Area Surveillance).

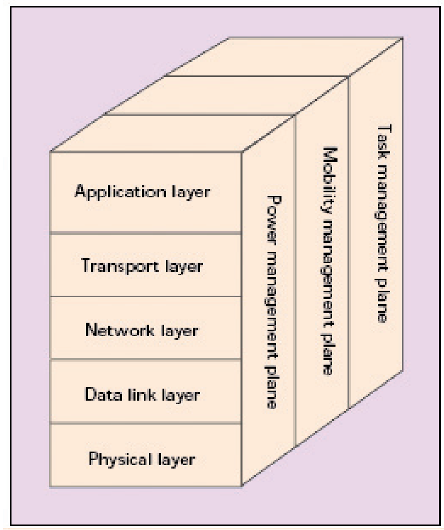

FIGURE 9 Protocol Stack for Harness project

Transmission protocol aspects

Recent advances in communications and electronics supplied low-power, multi-functional sensors and control nodes spread in integrated networks. These nodes consist of sensing, controlling, data processing, and communicating components.
Realizing these sensor network applications requires ad hoc networking techniques, especially underwater, where particular difficulties can be found. The protocol stack combines power and routing awareness, integrates data with protocols, communicates power efficiently, and promotes cooperative node efforts. It consists of the traditional layers: physical, data link, network, transport, and application layer as in Figure 9.
The "vertical" layers share information among all the traditional layers in order to improve the performance of the sensor & control nodes. The power management plane manages the node power. The mobility plane detects and registers the movement of nodes, so that a route back to the user is always maintained, and the sensor nodes keeps track of the neighbor sensor nodes.
The different data categories involve basically different requirements in terms of transmission range, priority, speed and allowed BER (bus error) so much that the category will also affect the MAC (medium access

control) and even the swarm configuration.
We basically consider four types of messages:
1. "sync" messages, i.e. the heartbeat of the system;
2. "sensorial" data, giving a picture of the environment as perceived by the many sensors of the swarm;
3. "supervision" messages, that are mainly addressed to the supervision station; they can include, for instance, video streams and commands;
4. "service and intelligence" messages, addressed to the other nodes to carry out system services like alerts of many types.

Control

The control system for 3D swarms, also in the underwater environment, is already a well-treated topic in literature; starting by the fundamental work of Bonabeau [8], several authors tried to cope with different aspects of the control problems like in [4, 8, 9]. We considered the ability of the swarm to react to the environmental stimuli and to mission modifications managed by several composite control layers of the Intelligence subsystem (Fig. 10).
The three main layers that we choose to introduce to achieve this result are:
- the Communication control,
- the Swarm control,
- the Individual control.

In addition a fourth layer, the Arbiter, solves conflicts that can arise among the previous levels:
The Intelligence architecture is based on a sort of MIMD architecture where each individual has the same processing hardware and the full potential processing functions.

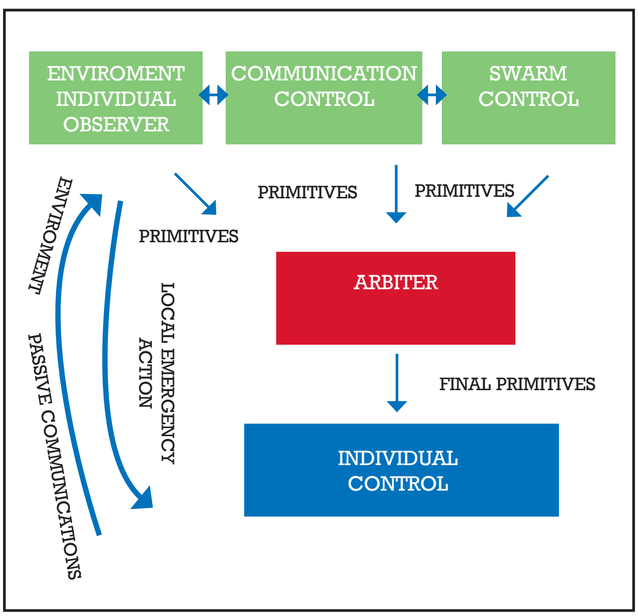

FIGURE 10 Principle control scheme

Communication Control

Communication is a part of the intelligence of the system able to give commands to the Swarm, just as the other parts of the Intelligence Subsystem.
Communication Intelligent Layer senses progressive degradations of data transmission efficiency and obtains by SC data of the environment adopting correcting measures, like the physical modification of the Swarm rule that controls the distance among the vessels. A classical discussion can be found in [6, 7], whereas a reference research has been carried out and recently presented [11, 13].

Swarm Control

The Swarm Control generates the primitives sent to the Individual Control for the planning of the trajectories.
A typical "primitive" rule could be: "bring the mean distance from your neighbors to less than 5 meters". This kind of rule (the Primitive) has no effect on the trajectory of an inner swarm individual since it lacks additional information. Other inputs are required and the rule system quickly becomes a relatively complex system. In this case a Direction Priority is required to address the Left/Right or Up/Down and the relevant versus.

Individual Control

Individual Control (IC) could be seen as a "classical" AUV control, able to carry out functions like path planning, collision avoidance, absolute and relative speed control, and so on.
Individual Control solves the problems and the conflicts relevant to the rules application like the obstacle collision avoidance. In this case a useful

strategy could bring to a separation of the school in two or more parts and the rejoining could generate conflicting situations [4, 10].

Arbiter

The Arbiter function represents a concept introduced to cope with the conflicts among different needs of the system and with the layers that take these needs into account.

Localisation

A living creature is typically aimed at fighting for food and standing by in the most convenient environment for the survival of the individual or of the group. Therefore in most cases it is more appropriate to talk about localization of the creature or Group inside a different space (space of the food – typically sensed by smell, space of the safety – identified by sensing the occurrence of possible threats, space of reproduction areas and so on). Of course, all of these spaces have their mapping into the geographical space. Rough, Precision and Relative Localisations are three different approaches that must be obtained for an effective navigation.

Rough Localisation

It is the capability of a Swarm to sense and identify non-metric features of the environment (refer to the aforementioned food space and others). This can be useful in carrying out surveillance missions of wide areas, when a precise localization is not useful during the whole mission, but only at the time when a target is identified. A possible light and cheap sensing equipment able to collect similar information is based on passive acoustical data. Typically the marine areas are acoustically mapped on the basis of their noise footprint and a large system like the Swarm is able to recognise the area location.

Precision Localisation

It can only be achieved endowing the vessels with Global Positioning System beacons and to elect some of the individuals to the role of surface navigators. The information exchanged through the network can allow for the geographical localization of the whole school.

Relative Localisation

Advanced algorithms, coping with the classical problem of trilateration but avoiding degenerate solutions, aimed at defining the relative position of each individual in the swarm to perform a task (i.e., define a trajectory implicitly or explicitly with respect to its mass center, define a space distribution, etc.). Cameras, pressure meters, compasses or acoustic devices can supply the information needed to fix the value of the distance from each individual to another and to establish absolute values (depths, speeds, angles with respect to the earth's magnetic field).

Teleoperation

Teleoperation represents one of the main targets of the research line. In environments like Underwater and Space, where delays and transmission bandpass are an important issue, the man-in-the-loop scheme asks for particular care. The classical approach of Teleoperation, an external sequence of orders, with a metrics inside, is not the best way to cope with a Swarm paradigm. Teleoperation can be maintained in its original form (remote operation replicated as if the operator is present on the place) if and only if the telecommunication properties allow the closure of the loop with an acceptable delay with respect to on-going task.

In any other case, the remote "slave" must be endowed with an increasing decisional capability so that teleoperation and telepresence become a new form of symbiosis, a telecooperation system that ranges, without sharp steps, between the two ending points of a complete autonomy and the true teleoperation. We define "high telecooperation level" a condition close to the true teleoperation, and "low telecooperation level" the condition approximating to the autonomous operation.

Conclusions

The system that ENEA is now testing has been considered as an interesting approach by many end users and in the next years the realization has been planned of some swarms to be built and tested under real operating conditions. At the same time, the more advanced functions relevant to communications, continuous connection to the surface, group intelligence and extended sensing will be developed to allow more powerful and advanced functions.

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