



# **HARNESS: A ROBOTIC SWARM TO EXPLORE AND PROTECT UNDERWATER CULTURAL HERITAGE**

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# **HARNESS: A ROBOTIC SWARM TO EXPLORE AND PROTECT UNDERWATER CULTURAL HERITAGE**

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## **ABSTRACT**

This work describes an underwater robotic system to be used for exploration, fruition and surveillance of underwater cultural heritage.

This system is based on a number of cheap autonomous underwater vehicles (AUV) organised on the swarm rules. Its development is currently in progress in our laboratory in the framework of the HARNESS project (Human telecontrolled Adaptive Robotic NETwork of SensorS) . The project aims at the realization of an underwater multi body robotic system able to perform tasks in a fast and reliable way. The key points of the HARNESS project are: the development of a novel underwater acoustic channel with very high performances in routing and data throughput capacities and the design of a reliable swarm rule-based control system with an interface towards a supervisor operator acting as a priority definition arbiter. The project includes a demonstration with a limited number of physical vehicles and with a larger number of simulated ones.

In a swarm the members operate with a common objective, sharing the job workload; the lack of one member can be easily taken care of by redistributing the job among the others. This feature is especially useful if we consider, as application the discovery and the surveillance of submarine archeological sites. Moreover a swarm can be considered as a single body, offering the advantage of a simple way of interfacing with the human end-users and overcoming the problem of the control of a large number of individuals. The geometrical distribution of the members of this system is flexible and adaptable to the task and environment characteristics. In the underwater world the physical medium makes the acoustical channels as the most convenient one, since electromagnetic waves are rapidly damped. The acoustical technology has limited performances too, being affected by a fast decrease in the signal bandpass (limited carried frequency) as the distance increase. The swarm technology allow to avoid this drawback by a suitable and intelligent spatial distribution of transmission nodes (the swarm members themselves), allowing the exploitation of ultra-high frequencies and an enhanced data transmission through logical and physical routing. One of the aims of the project is the study and implementation of different behaviors in the swarm, to generate a collective shaping as a response to environment stimuli and to modify of the communication parameters in order to maximize the performance of the system.

The swarm control must balance the different requests of the operator (e.g. modify the mission task), the swarm needs and the single members management (e.g. obstacle avoidance, loss of communication link). The result is the selection of collective behaviours that must be compatible with all the before mentioned conditions.. The methods currently under evaluation to this aim include neural network techniques, fuzzy logic and genetic algorithms.

In the swarm there is no central brain, mainly because of the excess needs in band pass requested by such a brain. Instead each individual must possess an intelligent local control system capable to manage its choices according to the choices of the neighbours on the basis of the available data. Data coherence along the swarm, being affected by the the position of the member and by the data propagation speed is also a research topic.

The foreseen applications of this underwater swarm are the safeguard of the underwater cultural heritage in terms of: exploration of submerged sites, searching for possible new relics, surveillance known sites against damage, realization of a remote museum facility where tourists and archaeologists can explore underwater sites without “getting wet”.

## **INTRODUCTION**

The importance of historical underwater sites holding valuable time capsules is strongly different along the world, but it is of the greatest relevance in Mediterranean Sea because of the

relevance of its history on the humankind evolution. The most interesting areas are those in proximity of the coasts and with depths ranging between 50 to 200 m. Because of the need for experienced divers after 30-40 meters explorations and owing to limitations to their operation effectiveness after 70-80 meters, recovery operations but also simple explorations becomes quickly highly expensive. In addition, the protection of the historical sites against robberies represents one of the most pressing concerns of the cultural heritage authorities.

The use of underwater autonomous vessels or rovers has been experienced and proven to be useful in some cases, but generally expensive mainly because asks for the support of an equipped ship.

The use of underwater robotic vehicles in ocean surveys, inspections, pipe and cable tracking, has been well established in the field of marine engineering since many years [1] (1). Today surveillance of ports and of other maritime environments, is assuming an increasing importance for naval and customs services [2] (2) Marine robotics technology had a very quick increase in performance in recent years [3] (4). and many autonomous underwater vehicle systems moved from the prototype stage to scientific, commercial, and military uses.

An AUV must be considered as a real cost alternative to other available technologies, such as manned submersibles, remotely operated vehicles (ROVs) and towed instruments led by ships. Anyway many problems are still to be solved for a full competitiveness of AUV technology especially for the issues relevant to the power availability, information processing, navigation, and control.

The use of a large number of very low cost [4] mini AUV could limit the use of the expensive surface ships to the deployment phase, taking advantage of the parallel exploration to shorten times. The availability of a suitable robotic swarm could be relevant in many operations: surveillance of sensitive sites, fast exploration of relatively wide interesting areas, detailed analysis of the goods without removing them from their underwater sites.

The concept of robot swarms is a study theme by the scientific community since several years. The realization of swarms of different numbers of cooperating robots has been successfully attempted, but in underwater environment it is still a challenge. Many of the difficulties coming from the unfriendly underwater environment are mainly focused on the problem of fast and reliable communication links. Swarm research has been inspired by biological behaviors, like the one of the bees [5, 6], since long time to take advantage by social activities concepts [7]: labor division, task cooperation and information sharing. A single-robot approach is affected by failures that may prevent the success of the whole task. On the contrary, a multi-robot approach can benefit by the parallelism of the operation and by the redundancy given by the usage of multiple agents.

A desirable issue is the system ability to adapt itself to the environmental characteristics, with special reference to the problems arising in the communication inter-individual and between the swarm and the human. These aspects are both related to the communication channel and to the geometrical distribution of the multi robot system [8]. In the underwater world there is an evident limitation to data throughput and temporal delay caused by the physical medium. The research aims at overcoming both limitation by means of an intelligent spatial distribution of transmission nodes (the swarm members themselves).

Depending on the salinity, the turbidity, the presence of dissolved substances that change the color and the transparency in different optical bands the bandpass can be heavily affected. Therefore communications can take place with greater or lower speed in the optical or acoustical domains, with different delays, attenuations, angular distributions of the radiated power and so forth. In other words there are almost continuous modifications of the acoustical and/or electromagnetic channel travelling from different areas, often quite close each other.

The multi body system can react to these modifications both modifying the parameters of its transmission "organs" and modifying the physical dispersion/geometry of the system itself. If the mission of the system asks for a greater dispersion in order to maximise the volume (See Figure 1) to be explored the communication bandpass could be slowed down and/or the main stream of the information can be differently balanced among the available channels (currently optical and acoustical) or possibly to Radio Frequency (in case of fresh waters for instance). If the priority is on the risk that the amount of exchanged information becomes inadequate to ensure the correct behaviour of the multi body, the system itself can physically react changing geometry despite of the drop in performances on the assigned task.

Situations like this one imply that the swarm control level and the local control level can originate conflictual situations relevant to the optimisation of global and local goals. The choice of the right strategy to manage and synchronise this multilevel adaptive system is still under investigation and will be explored in a much greater detail during the project development, but it clearly involves the definition of rules in explicit (expert system) or implicit (neural networks) form and should be capable of on-the-job learning.

In general, the test case of Harness is based on an underwater swarm of simple autonomous mobile communication nodes with sensing capabilities for environmental monitoring. The global control architecture will be built around three basic issues: the human supplied goals, the internal operational rules, ensuring stability and coordination of members behaviour through the communication network, the emergencies and automatic answers of the single.

In a previous work we have shown the robotic as support to cultural heritage conservation; it was concerning the possibility to realize the remote museum concept by robotic telepresence of the human in underwater or, generally, in environment where, for many reasons, human presence is not allowed.

## **THE HARNESS PROJECT**

The core of Harness project is aimed at the integration of the individual, collective and communication control levels in a multi robot system in order to ensure the full operation capabilities both from the point of view of the network efficiency and of the aspect of mission efficiency (adaptation to the environment). Natural examples (See Figure 2) represented a couple of typical situations.

In robotics, it is common to refer to this kind of organisation with the term of "swarms".

A possible efficient way to achieve this is to organise a number of cheap, small units able to change their relative cooperation modes, geometries and other functional parameters by means of relatively simple rules that every member of the "swarm" has to follow. Typical objective of these rules are the maintenance of group coherence, the capability to follow a common target, the ability to avoid foreseen or unforeseen obstacles, the ability to share and use data perceived by all the group member. All these group behaviours allow in an implicit way, usually called "emergent behaviour" to fit at best with the surrounding environment.

Just to fix some ideas we can imagine that we are dealing with a system of about 20 object; each object has a torpedo-like shape, about one meter in length and 0.2 meter in diameter. The distance between robots are between 2-3 meter and 50 meter. The maximum distance possible between two robots at the opposite side of the swarm is about 1000 meters, as a very particular alignment case; the average value of the distances depends by the task and water characteristics (opacity etc..) but can be assumed of about ten meters. Maximum speed should be about 3 knots. These numbers are relevant to "Venus", the AUV realized by ENEA (See Figure 3) to operate in low cost configurations as is the typical situation of Cultural Heritage application and that could be the single machine component of the swarm.

Harness is focused on the conception, realisation and testing of a novel control system. In this innovative approach the intelligence will be hosted independently on each member of the system that will be able to act as a common member or as the leading one depending of what the situation will ask for.

The group members are able to exchange information not only by passive means (vision, perception of pressure waves, etc..) but also by a communication network and by the integration of a human supervisor inside the control loop.

This type of human supervision (we define this a tele-cooperation mode), allow a significant capability to determine the swarm behaviour (in the “classical” swarm theory this is not allowed).

In our project the human supervisor, endowed with semantic interfaces, acts on the “needs” of the swarm and therefore can address and describe missions, modify the geometry arrangement exchanging pre-defined set of rules, receive rough or preprocessed data perceived by the swarm.

Thus the originality of this project is both in robotic organisation, and in the chosen approach to the control strategy. The idea is to merge and mediate among the three different needs expressed by the three different levels of control: the local guidance of the single robot (e.g. obstacle avoidance), the navigation and behavior of the swarm and the management of the communication network.

## **CHALLENGES OF THE RESEARCH**

The control of a system composed by a large number of mobile robots operating with a common objective and sharing the job workload without a specific and individual programming must take into account the paradigm of emergent behaviour. This is an unforeseen common “behavior” [9-11] of the multibody system that derives from the rules originally programmed with respect of specific situation (alarms, obstacles, etc...). Many studies have been carried out on this issue, but presently there is no general solution to address and program the arising of emergent behaviours.

The starting point is to consider the multi body swarm as a unique device with behaviour and reactions of a single creature. This means that every part of the intelligence of the swarm (communication management, low level control, high level control, HRI) must be strongly integrated and dependant by the other parts to ensure a correct operation. Because it doesn't exist a "central brain", each individual must own the whole intelligence system, whereas the data available to the single can be different depending on the position inside the swarm, on the data propagation speed and, in special cases, on the role of some individuals. This approach implies that, as in the natural evolution, a part of the foreseen research is focused on the efficiency of algorithm swarm whereas another part must be specialized to the peculiar environment where the system will be hosted in its normal operation.

Presently research topics in the area of underwater swarms are directed towards:

- algorithms for swarms of robots allowing scalable (multiresolution) perception (during exploration, searching, or monitoring) of sea areas.;
- active and passive localization of individuals with respect to neighbour vessels and of the whole swarm with respect to the environment;
- dynamical communication and routing protocols, which explicitly consider and adapt the current knowledge about the physical positions (including momentum and orientations) of individual nodes.

Scientific and technical challenges can be summarized in:

- individual control of small vessels;
- swarm control as a whole, taking into account the different level of needs;
- identification of minimal sensor sets for specific tasks;
- localization of individual small vessels with respect to their operating environment as well as with respect to other vessels of the swarm;
- establishment of communication methods characterised by fault tolerant algorithms, high frequency carrier, controlled distance modulating power;
- exploitation of the communication network for localization purposes;

To make possible the previous results the project also focus some technological goals that should characterise the design of an underwater "swarm oriented" robot:

- very agile;
    - Low cost
  - endowed with equipment for an easy, multi-level communication with its neighbours.
- Endowed with sensing equipment suitable for a "swarm" perception.

Other more typical features are:

- mechanically robust;
- equipped with sufficient computational power for any level of autonomy;
- equipped with efficient batteries for electrical power;
- supplied with robust motion control sub-systems;

## **A POSSIBLE APPROACH TO APPLICATION TARGETS: THE CASE OF CULTURAL HERITAGE**

The swarm concept is especially rich in terms of possible applications in the seas domain. The low cost of operation, the speed and the detail of discovery analysis that is possible to reach, the overall robustness of the system make it a good approach for a number of possible applications ranging from:

- Surveillance and protection of critical infrastructures (i.e. oil terminals) from unauthorized intrusions; (see Figure 3)
- Protection of environment in terms of pollution monitoring and prevention;
- Control of maritime traffic also in term of integrity check directly during ship docking with enormous economical savings both for the port and for ship time saving;
- Protection of war ships during peace-keeping missions;
- Farm fishing cultures monitoring and surveillance;

Among these and other possible applications the cultural heritage protection is not a minor application and can take great profit by the application of this technology.

In particular early discovery of ancient archaeological sites, study and characterization of the site or shipwreck, protection of the identified site and fruition of the submerged goods by means of the swarm observation capabilities are some of the most attractive services that this technology can offer.

Actually many techniques and instruments exist for underwater explorations, but their performance and possibility of deployment are limited and restricted to some specific applications, which do not match demands of underwater archaeology. A swarm of robot could be easily used for detection, characterization and surveillance of underwater cultural patrimony. Moreover it can also be useful to realize the remote museum concept, when working in telepresence mode.

In particular searching of unknown archaeological sites can be performed by a swarm equipped with sensors for bathymetry like Side Scan Sonar and with video cameras for close inspection. In this way, large areas are simultaneously monitored, which increases the probability of site detection in a cheap way. Many other sensors can be mounted if specific measurements are required. Low-cost underwater robotic units, in fact, are an alternative to the expensive equipped ship with ROV and professional divers. Operation of the robotic swarm can be controlled from a small boat, or from land in case of short distances of the coast, thus drastically reducing cost of logistics and environmental impact.

During standard navigation, geometry of the swarm and the relative distances of its elements are self-adapting, thus allowing the system to reach the optimum data transmission while mapping maximally large areas different instruments present on board.

Communication can be realized by active and passive acoustical methods, optical and electromagnetic (only on the surface).

A project has been presented to develop a powerful swarm-based tool for underwater cultural heritage investigations. Following this project a possible specialization for early detection could be the performed introducing the presence of a “Scout” and an “Eye”. One vessel containing high speed RF communication channel, called “Scout”, assures a continuous link between the Swarm and the supervision console. One member of the swarm, called “Eye”, is permanently connected to the “Scout” and normally navigates on sea surface at close distance from the previous vessel. It has an high resolution camera on board. Both Scout and Eye carry high precision GPS and in synergy they provide precise geo-referencing data of the whole robotic swarm.

In case of suspected confirmation of a sea bottom or sub bottom entity, the operator sends command to the swarm for close-by exploration (proximity configuration). The suspected area is then closely mapped at increased resolution while Eye descends close to the sea floor and transmit the corresponding video images. Thanks to “Eye”, high definition video streaming to the control console is obtained also from deep sites. This solution is fully competitive with the cable based ROV-mounted cameras, with advantage of increased panoramic view in proportion to number of swarm elements employed in the swarm.(See Figure 5)

Also if automatic decision is a swarm characteristic in case of detection of new sites it is better to have human supervision; therefore the system can also work in teleoperated mode. For other task, like surveillance the automation mode could be more useful. In the case of discovery of a new archaeological area, the exploration of the detected site may pass to the next phase of characterization and, later, to the surveillance phase .

Communication, Control, Localisation, Teleoperation represent the key points of the project.

The Swarm can be viewed as a wireless network of mobile nodes. So far it is able to adapt for different needs depending on the physical arrangement of the nodes geometry. As example the swarm can assume the pipe configuration, (to transmit high speed data along relatively long distance), disperse configuration (to enlarge the surveillance area with low band pass) or a particular configuration to increase the internal (to the swarm) bandpass in order to allow processing like data fusion coming from many sensors concentrated on the same target (Enhanced Data Fusion mode).

The control of the swarm is based on the management of three control layers: Communication control, Swarm control, and Individual control; an Arbiter will take care of the choices in case of conflicts among the different layers.

The localization problem is divided in three different categories corresponding to three different working scenario. Precise localization (the swarm working close the shipwreck), rough localization (the swarm is travelling towards the objective) and relative localization (the relative position of the swarm members).

Teleoperation is a different problem. It is usually intended to interact with the swarm to modify high level objectives. Nevertheless, because the swarm control is conceived to have a limited or null interactions with external “orders” we used the trick to process the requests of the supervisor by translating them into “needs”. These “needs” becomes internal behavioural rules of the swarm itself; after this translations they are “implanted” in every member of the swarm through the Communication Network modifying and superimposing themselves to the previous swarm reactions.

The project also includes the realization of a device simulator, the control of the performance of different approaches and select the final technological choice. Also very important is the development of novel and advanced algorithms that allows the communication on a multi hopped network based on a multiple transmission system (acoustical / electromagnetic).



## CONCLUSIONS

In this work we have explained as the Harness project could be useful to the archaeologist community. In the project we propose a swarm of underwater cooperating robot for early detection, characterization, surveillance and remote fruition of underwater sites. The advantages lie in the economy of the method, the parallelization of the task and the robustness of the system. The disadvantage is the major control difficulty of the swarm, lying in the presence of a new layer named as "Swarm control" which has different rules from the individual machine control. Many difficulties are to be studied, especially in communication between the swarm elements owing to the unfriendly environment.

Actual work is addressed to overcome the principal problems we encountered in the realization of the project that are, Communication, control, localization of the swarm inside the sea and telepresence of human operator.

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## FIGURES

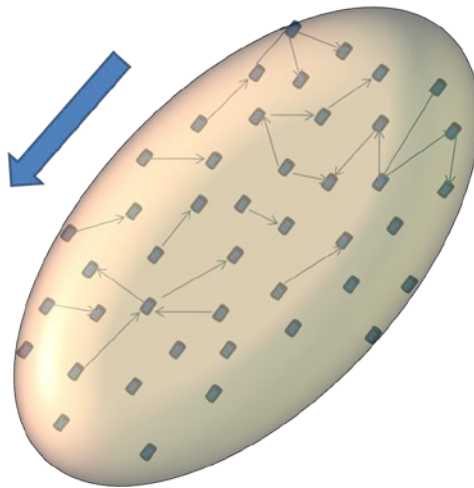


Figure 1a. “Ellipse” is a quite typical shape used in fish schools probably aimed at giving the most impressive

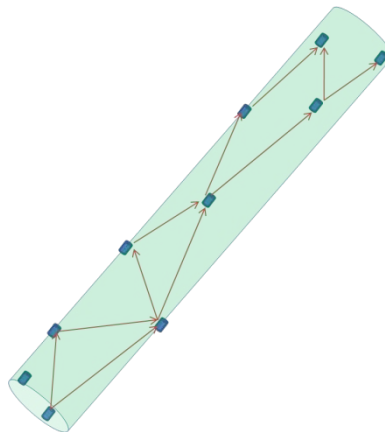


Figure 1b. “ This one on the right side is the “pipe”, where the communication is the main objective of the geometrical shape to transport data on long distances at the maximum allowed speed.

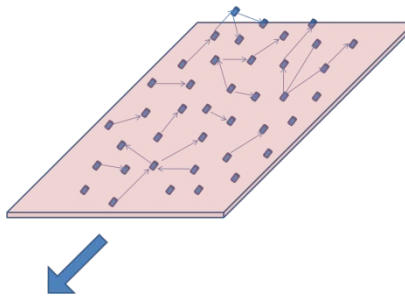


Figure 1b. Planar distribution to carry out fast and parallel monitor operations. The communication is especially aimed at allow an high rate exchange of information among the nodes



Figure 2a:adaptation of a bird swarm to environmental need (food hunting)



Figure 2b:Cylinder shape obtained by the internal rules of a swarm



Figure 3:low cost Venus AUV

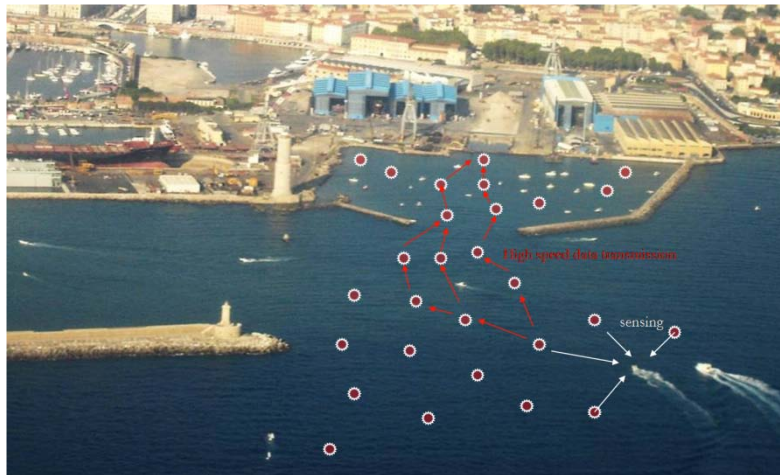


Figure 4: Surveillance in the Livorno Port (early warning)

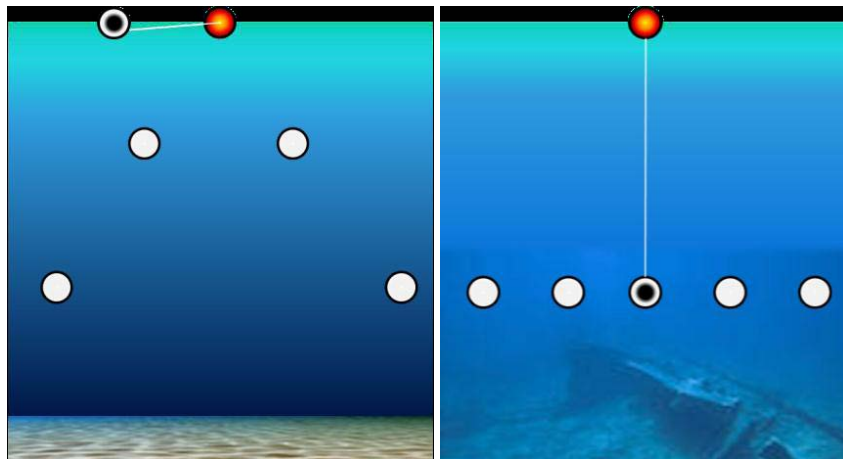


Figure 5: Swarm assets: left – standard navigation: right – proximity configuration