The Localization Problem for Harness: A Multipurpose Robotic Swarm

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***Abstract*—This paper deals with the localization problem of an underwater robotic swarm in the context of the HARNESS project (Human telecontrolled Adaptive Robotic Network of SensorS) currently in progress in our laboratory. This system is based on cheap autonomous underwater vehicles (AUV) organized with swarm rules and conceived to perform tasks, ranging from environmental monitoring to terrorism attack surveillance. The key aims 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 dealing with a supervisor operator acting as a priority definition arbiter. A method to determine the shape of the swarm, based on trilateration calculation, is proposed.**

Keywords-swarm; underwater; robot; localization.

I. INTRODUCTION

This paper deals with the localization problem of an underwater robotic swarm.

The HARNESS project [1] seeks to realize an underwater multi AUV robotic system, arranged in a swarm organization where the classical flocking rules and the Communication Network protocol are merged in a novel higher level control. It is expected to improve the performance of classical AUV technology exploiting the large occupied volume and the short distances among the vessels. The speed of surface monitoring and the transmission bandpass among the vessels and towards the surface should be some of the most important results. The availability of a suitable robotic swarm could be relevant in many operations: surveillance of sensitive sites, fast exploration of relatively wide areas of interest, detailed analysis of objects (i.e., archeological artifacts) without removing them from their underwater sites.

The most interesting areas to explore and protect are those in proximity to coasts and with depths ranging between 50 to 200 m. Professional and expensive divers can operate only to a maximum of 70-80 meters in recovery operations, and simple and fast explorations cannot be performed by humans beyond 100 m.

On the other hand the use of rovers has proven to be useful in many cases, but generally expensive mainly because they require the support of an equipped ship.

The use of robotic technologies in ocean surveys, inspections, pipe and cable tracking, has been well established in the field of marine engineering for many years [2] with an important increase in performance in recent years [3] as 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. However, many problems are still to be solved to make AUV competitive especially for the issues relevant to power availability, information processing, navigation, and control.

The goal of this paper is to give a presentation of the novel concepts in Harness. We will discuss advantages and drawbacks of the project concepts and explain the prototype under construction. Finally we will focus on the crucial problem of localization of the swarm with some proposal for an efficient solution suitable to some scenarios.

II. RELATED WORK

The expected features of Harness could limit the use of expensive surface ships to the deployment phase; moreover it takes advantage of the parallel exploration of many cheap AUVs [4] to reduce work time.

The concept of robot swarms has been a research theme of the scientific community for several years. The realization of swarms of different numbers of cooperating robots has been successfully attempted, but in the underwater environment it is still a challenge. Many of the difficulties are relevant to the lack of fast and reliable communication links. Swarm research has been inspired by biological behaviors, like the one of bees [5][6] to take advantage of social activity concepts [7], labor division, task cooperation and information sharing. A single-AUV approach is affected by operational limits the lack of effective communication and the limitation of available sensing that may reduce its effectiveness. On the contrary, a multi-robot approach can

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benefit from its parallel operation and from redundancy and greater robustness allowed by the use of multiple agents.

Another theoretical advantage of the swarm, considered as a whole entity that we intend to investigate lies in the possibility of performing parallel computation from realizing a distributed perception. As an example, landmark recognition is a task that can be shared among the different nodes taking advantage of the different viewpoints of the same target and applying a voting process to increase recognition performance. An adequate communication network must be available, in order to allow at least the exchange of the target identification features, but the network under design, based on multiple channels with carrier frequencies among 0,3 to 2 MHz promises to be adequate.

This form of distributed perception is a novel attempt that cannot be effectively demonstrated in a simulated scenario apart for the implementation aspects. The real experiment is therefore expected at the end of the project, in a couple of years' time, when a basic swarm of at least ten vessels with relevant sensors and communication network will be available

Another project strength is the capability to adopt a flexible geometrical distribution of the members depending on the task and environment characteristics in particular for communication. In the underwater world the physical medium makes the acoustical channel the most convenient one, since electromagnetic waves are very rapidly dampened. Acoustical propagation can offer better performance, but a number of effects must equally be taken into account. High frequency carriers are dampened too, even if less dramatically then their E.M. analogue. Moreover when the frequency increases, the propagation within the medium shows an extremely narrow direction pattern that prevents the easy dispatch of a message among the many nodes with mobile and imprecisely identified positions.

The solution of this puzzle takes advantage of the swarm organization and of the possibility of a mutual interaction between the spatial distribution of transmission nodes (the swarm members themselves) regulated by the flocking rules and the transmission protocol. In Figure 1 and Figure 2 two examples of adaptive localization of the swarm, for different tasks, are shown. The exploitation of ultra-high frequencies is enabled by the shortening of distances with positive effects also on the multi-path effect and the consequent intersymbolic interferences. On the other hand a task request for a wider swarm configuration can stimulate the flexible protocol to select lower frequencies and slow down the communication rate.

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 environmental stimula and to modify the communication parameters in order to maximize the performance of the system [8].

In this case the swarm control must balance the different requests of the operator (e.g., modify the mission task), the swarm needs and the single member's management (e.g., obstacle avoidance, loss of communication link).

The result is the selection of collective behaviors that must be compatible with all the aforementioned conditions. One of the peculiar approaches of Harness is the aim of controlling a swarm as a whole by a human supervisor. Because of the unique control concept of the swarm this action has to be carried out by means of a non-conventional procedure. Human commands, given in intrinsically fuzzy channels (gesture recognition / voice commands) are converted into flocking rule modifications. In this first phase the research is limited to the change of the rule parameters; the next step will be a selection from amongst a different set of rules; and the final goal (if the field tests clearly show the need) will be the automatic synthesis of special rules.

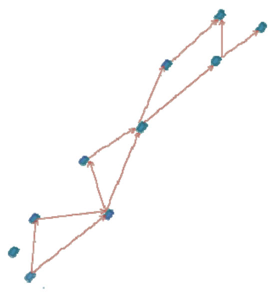

Figure 1. "Pipe", configuration indicates when the communication is the main objective of the geometrical shape to transport data on long distances at the maximum allowed speed.

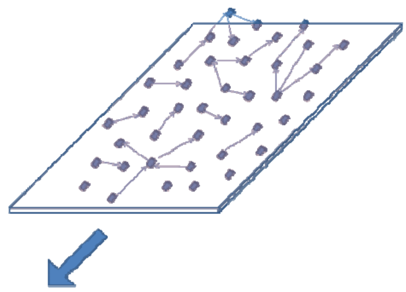

Figure 2. Planar distribution to carry out fast and parallel monitor operations.

The communication between swarm and human requires a special function. An element of the swarm has to emerge, navigate to the sea surface and activate an RF link with the console while it continues to maintain the link with the other elements.

III. THE SWARM VESSEL PROTOTYPE

In Figure 3 the Venus prototype, a torpedo type realized in our laboratory, is shown. Its characteristics are the following:

Max depth 100m; Max speed 2 Knots; Weight about 20 Kg; Autonomy 3hrs; Dimensions 1.20 m length 0.20 m diameter.

Standard sensors include a stereoscopic camera, sonar, accelerometer, compass, depth meter, hydrophones side-scan sonar.

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Figure 3. Low cost Venus AUV

We are dealing with a system thought to be a component of a swarm of about 20 objects. The distances between robots ranging between 3 and 50 meters. Therefore, the maximum distance possible between two robots is about 1000 meters, as a very particular alignment case; the average value of the distances is about 10 meters. Maximum speed should be about 2 knots.

An optical, high power, transmission device will be used for a number of different experimental approaches integrating the acoustical data channel and the direct vision sensing.

Optical methods are very powerful but their performances are affected by many strongly variable parameters like salinity, turbidity, the presence of dissolved substances that change the color and the transparency in different optical bands and the amount of solar radiation that heavily affect the signal to noise ratio.

The current approach uses a strategy based on the variable exploitation of the optical channel depending on the environmental conditions. In favorable conditions the transmission protocol will freely decide which channel to adopt depending on the priority, distance-to-cover and dimension of the message itself. In less favorable conditions the optical channel will be limited to the fundamental synchronization task, generating a light lamp that will optimize the message passing through the optical channel (and several other non strictly communicating functions). In poor optical conditions strong but very short lamps, will ensure references for a safer visual navigation.

IV. THE LOCALIZATION PROBLEM

Localization and mapping is the key of a successful navigation in autonomous mobile platform technology and is a fundamental task in order to achieve high levels of robustness in vehicle positioning and values of the collected data. Robot localization and mapping is commonly related to cartography, not only for geographic purposes, but for biological and ecological studies, for geophysical researches and for security surveillance. It combines science, technique and computation to build an environment representation to correlate spatial information with the data collected [5][6].

Compared to a single AUV, a multibody system has the need to know and manage its own configuration. This can be an advantage if we are able to profit from the large number of data points to reduce errors in positioning. The localization problem of a swarm can be divided into three tasks:

1. Absolute localization, with the meaning of localization of a member or of a geometrical locus with respect to a fixed reference system (AL)
2. Relative localization of (RL) i.e., the swarm configuration.
3. Relative localization of one member with respect to neighbors; we call it immediate relative localization (IRL) and its meaning will be clarified later.

Different methodologies are required to solve the three tasks. In line with the swarm philosophy each element must be able, if connected with the others, to perform the localization task. However, the reader's attention is drawn to this last point. We do not mean that each element must always do all of the tasks; often there is no need to know all of the machines' positions, but each vessel must be capable of doing so using all the internal data, the external data communicated by the other elements and the external data measured by the robots, including that deduced by environmental observation.

The usefulness of IRL is in achieving a rapid response to environmental modifications. If the system has to wait for a thorough knowledge of its internal structure before deciding the type of response the reaction times could become too slow, compared to the dynamics of environmental phenomena.

Schools of fishes change their position in a very quick time just looking the movement of the neighbors. In principle also IRL is more easily achieved with simple and robust signals based on physical fast transient, and possibly using a rapid propagation of fields such as optical. Later, if necessary, the swarm can re-compute the relative position of each member.

The knowledge of the whole configuration can be useful, for instance, in some approaches to the geographic identification of a site: the possibility to collect information from many "points of view", by a swarm, allows a "distributed site recognition" (a task that we are starting to study). This technique leads to landmark recognition with less ambiguity. We distinguish the problems because they are separate: localization of a single entity is a problem relevant to understanding a metric of the space, possibly realized only by a sequence of reference points, and to placing the entity in relation to the established metrics or with to reference points. Localization of a swarm underlines the different techniques that can be used together with the different information that can be gained.

For many animals localization may be related to different types of metric linked to the search for something critical for their life like food. In fact this localization could relate to the identification of a source of chemical compound that is attractive for the biological or robotic system (which could be blood to indicate food or something else indicating pollution); the result is a physical field with gradients of arbitrarily complex shape. Our position is therefore referred to the smell, great or small, of our reference parameters. We can move toward the higher value of the field to reach the source. In this case the geometric or geographic location is meaningless for the success of the mission except when the mission itself is finished and the last task is the site

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identification for further actions. We are locating ourselves in the higher concentration food position.

The previous example of gradient localization is an example of topological localization. Its realization is similar to the force field potential applied in many obstacle avoidance techniques.

Two different environment representations can be used: metric and topological world models. A metric environment map, using a unique coordinate system, is theoretically easy to implement when you are using distance sensors. However, metric maps are not well suited to integrate non-metric information as required if you have to match patterns. Moreover, metrically consistent map building is a non-trivial problem.

Topological representation models of the world make use of graphs of nodes (distinctive places) and connecting edges (pathways). The advantage is simplified map building (path planning is reduced to direct graph search); moreover sensor fusion of non-metric and metric data is easier, because they are uniformly treated as attributes to nodes and/or edges.

However, topological world models, typically, are characterized by poor resolution, which is insufficient for any other purpose than navigating from one region to another.

Another example is the kinesthetic sense of human body; it works with a sensitivity to muscle tension and extension; the brain relates these variables to locate the position of the body in space.

It is important to note that such a kind of a map is a multidimensional set of associations of features (houses, streams, odors) with usually non-linear metrics that allow you to switch gradually from a certain place to another place via a route typically, but not necessarily, geographical.

Localization of a swarm encompasses different techniques that can be used together with the different information that can be gained by putting them together. This can become a great advantage.

The easiest localization system is the open loop estimation; this means that the estimate of position is based on expected results of motion commands. Therefore no contribution from the sensor is required and no feedback is calculated.

The information that the robot gathers can be divided into two kinds; idiothetic and allothetic sources. The distinction relates to internal or external sensor source data; as an example, if a robot is counting the number of wheel turns this is an internal source.

The allothetic source corresponds to the sensors of the robot, like a camera, a microphone, laser or sonar. A typical problem of this last method is "perceptual aliasing"; this means that two different places can be perceived as the same. For example, in a building, it may be impossible to determine your location (sometimes also for humans relying solely on visual information, because all the corridors may look the same). Without an external reference, like for example, acoustic beacons at known positions, the vehicle has to rely on proprioceptive information obtained through a compass, a Doppler Velocity Logger (DVL) or an Inertial Navigation System (INS) [6]. To this, totally internal to the robot family belongs one of commonest methods, the dead reckoning [9.

A common dead reckoning sensor is the INS. An INS measures the linear acceleration and the angular velocity of the vehicle using three accelerometers and three gyroscopes. Typical underwater external sensors used to correct accumulated errors from the integration of the INS measurements, are Doppler Velocity Log Sensors (DVL), Ultra Short Baseline (USBL) and Differential Global Position Systems (DGPS/GPS); the latter only in the case that the vehicle is operating in shallow waters and can come out of the water to fix (and eventually communicate) the position.

Independent of the quality of the sensors used, the error in the position estimate based on dead-reckoning information grows without upper limit. Typical navigation errors are about some per cent of distance traveled for vehicles traveling within 100 meters of sea. Lower errors can be obtained with large and expensive INS systems, but for vehicles relying only on a compass and a speed estimate these can be higher than 10%, after 100 meters. The error can be reset if the AUV comes to the surface by GPS, but sometimes this is impossible (under ice for example) or undesirable (security operation) [8]. The use of beacons to form a Long Baseline (LBL) array limits the operation area to a few square kilometers and requires a substantial deployment effort, to position the beacons, before operations, especially in deep water. This reduces the advantages of AUV and requires an expensive ship to support the operation. A swarm could be advantageous compared to a single vessel, if a high rate of communication is available, to reduce the dead reckoning errors. It can collect together all the data of all the vessels to minimize the errors in estimating position.

Other methods employ the use of landmarks. If we use external references in the localization problem, like humans, we have to deal with their definitions and position on a map (metric or not). Any kind of landmark is subject to classification and identification based on its attributes. Unfortunately the identification and positioning of a landmark often suffers from ambiguity, owing to the multiple solutions of the associate equations. That has the meaning of more than one landmark is identified by the same features.

A set of features' location position estimates can basically be thought of as a map. The challenge is to combine INS/dead-reckoning and other information with sensor observations of features to build a map, locally or globally referenced.

A more modern idea consists of matching measurements of one or more geophysical properties, such as bathymetry, gravity, or magnetic field, to a known environment map. If there is sufficient spatial variation in the parameters being measured, there is potential to reduce navigation uncertainty. As an example the marine turtle's migration is monitored by magnetometers, measuring the earth's magnetic field variations. However, often, these techniques require a map of the environment that is not available. The marine turtle's migrations are monitored by a three axis magnetometer, but the method's resolution is only 35 nautical miles [10][11].

V. OUR PROPOSAL

If we have three or (better) four vessels on the surface they can be positioned by GPS [12]. Later, using the communication system, we can obtained (i.e., from the clock time of each communications between the elements) the distance between one or more vessels and the "constellation" whose position is known. Using the same mathematical calculation of the GPS system we can get the Absolute Localization of the whole swarm. The vessels on the surface (that can be substituted by little boats) could also have the advantage to carry a high band pass using laser communication system, owing to the easy transmission vertical channel; in fact the collimation problem (typical in laser communication systems) between vessels, in this case, can be partially avoided .

If we do not have surface vessels we can calculate the Relative Localization (i.e., the configuration of the swarm) solving the distance equations and using a constellation composed by some vessels; unfortunately we have multiple possible solutions and to select between them we need some more information. A flash, for example, can be used to discriminate direction from which the signal has arrived. A more clever system is to use a whatever (but known) movement of the swarm and to repeat the calculation for multiple solutions corresponding to the new possible configutation. Now, using the preceding configuration and appliyng a coordinate transformation (from the known movement), we obtain only one configuration matching both the old and the new. At this point we can obtain the configuration of these elements of the swarm taking one of them as the coordinate origin. Later, when the distances of other vessels are available, we can add more elements to build the whole swarm configuration.

VI. EQUIPMENT

The equipment to perform these solutions divide into "base requirements", which is the minimum instrumentation we anticipate having on the single machine and "desirable requirements" for enhanced instrumentation and better performance. Quantitative considerations are not considered here due to lack of space.

Each machine is characterized by six degrees of freedom, but only two of them (depth and heading) are very easy to measure, by means of a depthmeter and a compass. If the machine has cylindrical symmetry one is uninfluenced. Considering the yaw to be unimportant (we imagine navigation in one plane other than for a few moments) we understand that the real difficultly is to determine the coordinate x-y, of the center of mass; the x-y plane being that parallel to the sea bottom.

The base equipment of all the machines is composed of: Network communication, GPS, Depth meter, Inclinometer, Compass, Flash, Photodiode, Webcamera, Livery on the vessel surface and an electric or magnet device. All these components are cheap and available.

The network is a requirement that exists not only for communications but must also be used for data exchange and we are interested in its use in sonar ranging for RL. Of course a snapshot of any situation suffered in a delay, we presume between tenths of a second and one second, should be sent, together with the estimated robot speed for the correction. The network should be able to shift the working frequency from 100 to 1000 Khz (at least two frequencies). This number comes out from the consideration of data rate and the use of the net as an emergency ping or localization signal. The distance we want to cover (maximum 50 meters) and the data rate should be between 10 and 100 Kbytes/sec.

All the data available will be fused and weighted with all the data coming from other instruments so as to be more precise in localization. More than one algorithm is desirable, for example one which is more complex that uses all the available data and one which is quicker using only a subset of data, depending on the operative conditions and on the kind of localization required.

GPS is used for AL, when a scout (single robot that has this task) is on the surface.

At least a commercial depth meter must be present for AL in one dimension.

A couple of inclinometers is useful to measure the angle of position with respect of the land. Another degree of freedom can be removed by compass; care must be used in case of the presence of magnetic disturbances.

A photo-diode is used to receive flash lamp sequences for light communication; for example a codified sequence could send the heading of one machine to the other (close neighbors) so as to adapt themselves. Therefore, to transmit a simply codified message by flash, we can transmit a sequence; working on color or flash time is more complicated, standing the use of a cheaper flash unit. In some cases we can use an optical modem. This is a very cheap and light instrument, but does not give information on the position of the light source.

A webcamera must be used for image recording. Moreover together with an optical flash lamp. Using omnidirectional vision it is possible, with synchronized flash (or triggered by the first flash and using cumulative vision over a few seconds) to get qualitative information on the density of the machines. Of course it is not metric information but the single machine can get information if it is far or too far to the left (for example) from the swarm. Moreover flash could be useful in rescuing a single machine in difficulty, together with a switch of the network toward lower frequency working so as to increase the range.

The camera can also be used in the livery lecture for IRL for fast reaction movement, but it requires a computational job that must be simplified; image analysis is much too heavy. This last task could be done as a batch as for Simultaneous Localization and Mapping (SLAM), distributing the computational cost on a parallelized machine (the swarm itself if the network is adequate).

The single machine can be equipped with a strong electromagnet. The advantage of a static magnetic field is the possibility of transmiting (like a flash sequence) some information to the other machines. Moreover the hope is, contrary to the light source, to get some quantitative information on the RL by means of the magnetic field vector.

Electromagnetic transmission in sea water has made some progress over the last few years. Some opportunities are under investigation [13][14].

Magnetic (and electric) methods require some further consideration. An attempt to localize Rfid by magnetic field has been performed in air [13]. We start by considering the Earth’s magnetic intensity field. Its scalar value is about 20 microTesla at the equator and 70 microTesla at the poles. We can consider it constant in our area of operation with some exceptions. We can generate a perturbation in magnetic Earth field to get information on the perturbation position (distance or heading direction or some other) from these numbers. We have calculated that cheap magnetometers are able to do this (also taking in account natural anomalies of the magnetic earth). So far, we should now be able to detect the spike in the magnetic field (we have calculated it in some conditions) superimposed on the Earth's field that we have generated in the sea. We get no information from the transient of the field but we do measure a change in the magnetic Earth fields. We now have two opportunities; one is a slow modulation of the field (to reduce attenuation) carrying some codified information, such as flash lamp. The second is to make an attempt to calculate the position of the field generator. This has been done for two objects in open space. It is a greater challenge to do this for a multisystem in the sea. We are investigating this possibility. Some other equipment such as Acoustic pinger, LBL USBL device, DVL, AHRS, Electromagnetic devices, Gradient localization can increase the performance of the system. A harbor could be equipped at not so high a cost, compared to the normal cost of surveillance. DVL can be mounted to integrate its data with cheaper AHRS (like XSense for example) for AL and RL (we avoid INS for the cost). A quantitative measure of absorption of electromagnetic waves in the water led to the possibility of using Radio frequency modems in sea water. Anyway some new electromagnetic underwater modems may promise something here and we are investigating. Recently, electromagnetic devices for marine application have shown an improvement in their performance leading to commercial products [15]. These new devices need to be investigated and also whether their dimensions are too large for Harness project. Electric and static magnetic fields also are under investigation.

VII. Conclusion and Future Work

In this work, we have explained that the Harness project could be useful for multipurpose use with particular attention to the localization problem. We propose a swarm of underwater cooperating robots.

The advantages lie in the economy of the method, the parallelization of the task and the robustness of the system. The disadvantage lies in the major control difficulty of the swarm, owing to the presence of a new layer named as “Swarm control” which has different rules from the individual machine control. Many difficulties remain to be studied, especially in the communication between swarm elements owing to the unfriendly environment that limits the communication channel also if different methods are used together.

The localization problem is divided into three different tasks related to different work conditions and some classical and alternative methods are under investigation. The configuration problem of the swarm is solved using the time clock of every message exchanged between the elements of the swarm and its known movement. 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 within the sea and telepresence of the human operator.

Future work will concern the realization of a demonstration by using three prototypes.

VIII. Acknowledgments

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