AN APPROACH TO UNDERWATER SLAM USING MECHANICAL SCANNING SONAR

G. Conte, S. M. Zanoli, L. Gambella, D. Scaradozzi

Università Politecnica delle Marche
Dipartimento di Ingegneria Informatica, Gestionale e Automatica "M. Panti"
Via Brecce Bianche – 60161 Ancona – ITALY
{gconte, s.zanoli, d.scaradozzi}@univpm.it - *gambella@diiga.univpm.it*

Abstract: This work aims to assess potentialities and limits of a Simultaneous Localization and Mapping (SLAM) technique in underwater environments. Sonar data are used to build environmental map in form of evidence grid and information about the vehicle's attitude, coming from a compass, is integrated in the process of matching local maps. Performances of the proposed procedure have been tested in a pool and accurate measurements have been taken in order to evaluate quantitatively the results. Localization errors for the position of landmarks and of the vehicle turn out to be comparable with the intrinsic uncertainty in sonar data.

Keywords: SLAM, Underwater robotics, Robot navigation, Navigation, Marine systems.

1. INTRODUCTION

The aim of this work is to assess experimentally potentialities and limits of a Simultaneous Localization and Mapping (SLAM) technique implemented in underwater environments by small class, cost-limited unmanned underwater vehicles.
In general, the SLAM problem for an agent in an unknown environment consists in building incrementally a map of the surrounding environment and in computing, simultaneously, its own location on the map. This problem may be approached in several different ways, according to the sensory system of the agent, to the chosen representation of the environment and to other requirements and constraints. In literature, approaches to the underwater SLAM problem have been proposed in (Leonard, *et al.*, 1995), (Newman, 1999), (Williams, *et al.*, 2000), (Tena Ruiz, *et al.*, 2001), (Dissanayake, *et al.*, 2001). The considered sensory system usually consists of sonar sensors and the environment is represented, in general, by means of feature maps. Techniques based on the construction of evidence grid and the use sonar in indoor environments are described in (Moravec, *et al.*, 1984), (Elfes, 1987), (Elfes, 1989), (Martin, *et al.*, 1996), (Schultz, *et al.*, 1998), while feature maps in indoor environments are used in (Leonard, *et al.*, 1992), (Schiele, *et al.*, 1994), (Gutmann, *et al.*, 1996), (Thrun, *et al.*, 1998).
In our approach, we consider the situation in which an underwater vehicle, actually a Remotely Operated Vehicle (ROV), has to map a simple, static environment and to localize itself in it. The sensor used for exploring the environment is a mechanical scanning, single beam, imaging sonar mounted on board. This device provides a sort of acoustic image of the surroundings, since it measures the intensity of the return signal from definite regions of the explored area, giving more information than simple range measurements. Sonar data are used to build environmental map in form of evidence grid and information about the vehicle's attitude, coming from

a compass, is integrated in the process of matching local maps, improving resolution and limiting computational burden. The environment is represented by a grid map, as this choice allows to exploit fully the available information and it fits well with its inherent discretization.

In this paper, the experimental work initiated in (Conte, *et al.*, 2006a), (Conte, *et al.*, 2006b) is improved under some aspects. Sonar data processing is performed both at low level and at high logical level in order toreduce the effect of noise, to avoid false echoes and to get more realistic maps of the environment. In addition accurate measurements are performed in order to evaluate quantitatively SLAM results with respect to the actual position of landmarks and of the vehicle. The performances of the adopted procedure have been tested in a pool with artificial landmark.

The localization and map building problem we consider is illustrated in greater detail in Section 2, where also the experimental apparatus is described briefly. Essentially, the ROV is assumed to take a scan of the environment from its current position and this is used to build a local map. Then, the ROV moves to a different position and it takes another scan. The last scan is matched together with the previous one, updating the contained information and allowing to build incrementally a global map. The orientation of the ROV, and hence of the sonar, is measured, during the scan, by a compass and this information is instrumentally used in dealing with the matching problem.By solving the matching problem, the ROV localization problem is also solved. The main idea we exploit here, is the fact that acoustic images do not present perspective deformation, hence the matching problem is consistent. The data processing, as well as the procedure for building local maps and for matching them together, so to construct a global map, are discussed in Section 3. Finally, some experimental results in an emulation environment are shown in Section 4.

2. PROBLEM DESCRIPTION

The underwater environment we consider is assumed to be static, so that relative distances between objects in the scene do not change over time. The objects that populate the scene are assumed to extend vertically and to have a cylindrical shape, while the ROV is supposed to move on an horizontal plane at constant depth. This scenario models the situation in which the ROV moves close to the piles which support an off-shore platform and it is asked to map the area and to localize itself. Since the region to be mapped can be viewed as limited by two horizontal planes and the objects are vertical cylinders, we can conveniently represent it by means of a two dimensional map.

The information to be processed consists essentially of data collected from the sonar, while a compass is used to refer each sonar beam to the North. A ping of the sonar produces a return signal that is acquired, by the imaging sonar, as a series of echoes, called bins, each one coming from a region of space whose shape and dimensions depend on the shape of the emitted acoustic beam, on the distance and on other parameters. In particular, in setting the operative conditions of the sonar, one can chose a maximum range, that defines the extension of the region explored by a single ping, and a sampling resolution, that defines the extension of the region originating a bin in the direction of the beam. The number of bins results in an obvious way. The value of intensity of the echo depends on the presence of reflecting objects and on their characteristics like substance, shape, roughness and it ranges from 0 (no return) to 255. The characteristics of the available data, in particular the fact that the position of a reflecting object is quantized in relation to the chosen sampling resolution, fit well with the use of an evidence grid map. The dimensions of the single cells in the grid map are chosen according to the sampling resolution and the information is obtained by interpreting the intensity of the return echoes in terms of probability of occupancy

The sonar used in the experiments is a Kongsberg-Symrad MS 1000, with a head that generates a conic beam having a width of 2.7°. This configuration has been chosen since the experiments are performed in a pool of limited depth, where the use of a conic beam allows to avoid reflection from the bottom and from the surface. The sonar head can mechanically scan a sector from 0° to 360°, with a minimum scanning step of 0.45°. Contiguous acoustics beams may partially overlap and this fact is exploited in reinforcing the information in the construction of local maps, as described in the next Section. The time required to scan a given sector depends on its width and on the chosen range and sampling resolution. In order to assure a coherent interpretation of the acquired data, it is assumed that the vehicle motion during the acquisition phase is negligible, so that each single beam can be considered as originating from the same point.

3. DATA PROCESSING AND MAP BUILDING

The proposed SLAM technique is implemented by iterating a series of operations which consist in:

1. constructing a local map (referred to the vehicle point of view), using the information coming from the sonar;

2. matching the actual local map against the global map obtained at the end of the preceding iteration, so to satisfy a best matching condition;

3. gluing the actual local map together with the global map, according to the result of the previous operation, so to evaluate the ROV position, and updating the information on the global map.

At the beginning, when no global map is yet available, the local map just constructed is retained.

3.1 Sonar data processing.

Before implementing point 1, raw sonar data are processed at low level and high level, in order to reduce environmental noise (low frequency and high frequency noise), false returns due to the transient behaviour of the ceramic transducer in the sonar head and false (multiple) echoes (Newman, 1999), (Gambella, 2005). Figure 1 depicts a raw sonar return signal by showing the intensity values of the series of bins corresponding to a single ping. In this case the range is 5m and the sampling resolution 0.1m. Raw data are processed in four different was. First, an operation of masking is used to cancel the influence of the transient behaviour of the ceramic transducer, which originates the high intensity returns in the first bins. Then, an operation of thresholding is used to reduce environmental low frequency noise. The third step in the sonar data processing is an operation of peak smoothing in order to remove large amplitude, high frequency noise. Finally, to remove false echoes from the sonar data, an high level logical filtering is performed. The filter we use is based on the fact that real obstacles may give rise to a secondary acoustic image at double distance from the sonar head. By this observation, the implementation of the logical filter consists basically in detecting the first group of closely grouped bins which exceed a fixed threshold and in discarding the following ones. An example of the effect of the processing (masking, thresholding, smoothing and logical filtering) is shown in Figure 2.

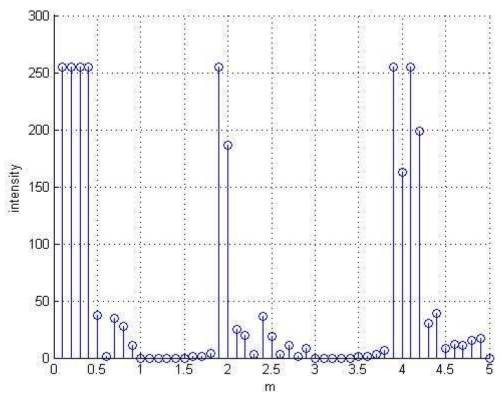

Figure 1 - Raw sonar return signal.

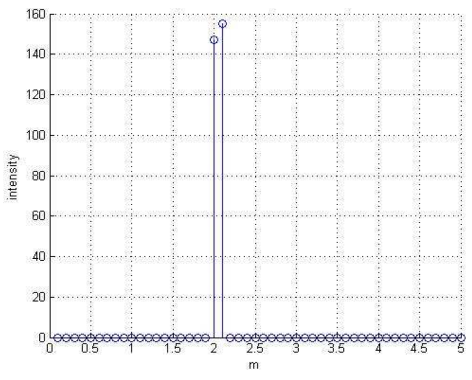

Figure 2 - Sonar return signal after low level and high level logical filtering.

Although the action of the logical filtering could mask the presence of real objects, this negative effect is of limited relevance in the construction of a global map when several scans of the same region are taken from different positions.
After the processing is completed, the resulting filtered series of bins can be viewed as an acoustic image of the explored region.

3.2 Local map building.

After filtering, from the acoustic images that correspond to each ping it is easy to construct a planar, polar map, whose cells are determined by the chosen scanning step and sampling resolution. The value of intensity of the return echo is associated to each cell and, in case of overlapping beams, the value given to the cell is computed by a process of weighed average. After normalization, the value assigned to each cell may be interpreted as probability of occupancy.
Using the information coming from the compass, the polar map is then converted into an oriented grid map, whose resolution is comparable, but may be different, from that of the polar map. Conversion is simply made by superposing the polar map to the grid with the correct orientation (the grid is conventionally assumed to be oriented towards North), in such a way that the center of the polar map, where the ROV is located, coincides with a conventionally chosen point.

3.3 Global map building and localization.

The next operation, corresponding to point 2 above, is to match the local map against the global one that comes from the previous iteration. The occupancy values associated to each cell, both in the local and in the global map, are thresholded and binary quantised in order to retain only the relevant information and to simplify the matching problem. In this way, one obtain two coarse maps, where free cells are given the value 0, while occupied cells are given the value 1. Matching is then performed by superposing the coarse local map onto the coarse global one in all possible positions which respect orientation and in evaluating a functional which sums the products of the values of corresponding cells. This procedure is justified by the fact that acoustic images, like those obtained by the sonar, do not present perspective deformation. Therefore, except for false echoes, due to multiple refraction of the acoustic signal, and environmental and sensory noise, acoustic images of the same region, theoretically, match perfectly when they are correctly superposed. Maps can then be superposed in such a way to get the best matching and the mosaic obtained by gluing them together in the configuration corresponding to the best matching represents a global map of the region.
In our situation, the best matching of two coarse maps is obtained when the largest number of occupied cells in the two grids coincides. False echoes and environmental and sensory noise prevent,

in facts, to have a perfect matching. Since the orientation of the maps is known, in looking for the best matching there are only two degrees of freedom and the search is performed by shifting one map horizontally and vertically over the other, in such a way to have, at least, a partial overlapping. The index of matching is easily calculated by multiplying the values of overlapping cells in the two maps. The result is 1 if and only if both cells are occupied, 0 otherwise, so that the sum of the results is maximum in case of best matching.
After the best matching problem has been solved, the two original maps at issue, that is those available before thresolding and quantisation of the occupancy values, are glued together in the configuration corresponding to the best matching. Since the position of the vehicle is know in each local map, the matching procedure allows one to plot the current position of the vehicle, that is the position where the last acquisition of acoustic data has been made, on the global map constructed so far. In addition, the occupancy values in the new global map can now be updated using the information contained in the local map. For the cells which belong to both maps and overlap in the one obtained by gluing, the update procedure that has been implemented computes a new occupancy value by means of the following formula, where g denotes the occupancy value on the global map and l denotes the occupancy value on the local one:

$$g_{new} = g + l - g \times l.$$

It has to be noted that this choice is quite conservative, since according to it the occupancy value cannot decrease. Although this can be useful to assure a safe navigation, it is clear that after several iterations the map may become inconsistent. Other strategies for updating the occupancy values in the global maps can however be chosen, according to differnt objectives and constraints.

4. EXPERIMENTAL RESULTS

In order to limit costs, experimental tests of the proposed technique have been performed in a circular pool (16m diameter, 1.4m depth) containing a number of objects (obstacles or artificial landmarks), consisting of PVC pipes (20cm diameter, 1.40m length) in vertical position (see Figure 3).
The test environment turns out to be quite noisy, due to multiple reflections, and, in spite of low level filtering, this may influence significantly the performances.
Here, we report the results of one experiment in which three objects have been considered and seven acquisition phases from different positions have been performed. The actual positions of the objects and of the ROV have been measured and the measurements have been compared, as explained later on, with the estimated values. Acoustic data have been collected setting the maximum range equal to 5m and the sampling resolution equal to 0.05m.

Figure 3. Test area.

Figure 4 shows a thresholded and quantized version of the global map obtained after iterating seven times the procedure described in Section 3. Cells in the map have dimension 0.05m × 0.05m. Two of the three object give rise to a set of closely grouped occupied cells, while, due to noise and false echoes, the third gives rise to a scattered group.

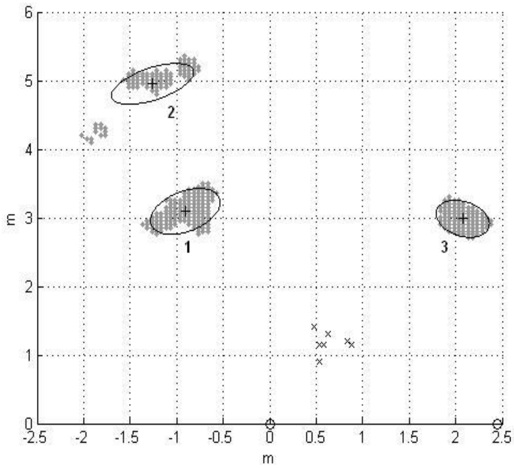

Figure 4. global map after seven acquisition phases.

In order to evaluate quantitatively the performances of the proposed procedure, an estimated position of the objects has been computed by implementing a K-means clustering algorithm. In doing this, we have used an a-priori information about the number of objects, that, in any case, does not play any role in the construction of the global map and in the localization of the ROV. The centroids of the clusters are assumed to indicate the position of the objects.
The various positions of the ROV during the acquisition phases are indicated by small “x”.
The object localization errors, namely the differences between the estimated positions of the objects and the measured ones, as resulting at the end of each phase of acquisition and of map building, are plotted in Figure 5 - 7.
Table 1 allows one to compare the measured position of the ROV during each acquisition phase and the estimated one at the end of the phase.
Errors in the position of the objects remains

relatively small and their magnitude is comparable with the chosen sampling resolution. The error in the estimated position of the ROV appears to be subject to larger oscillations.

4. CONCLUSIONS

In conclusion, the proposed SLAM procedure has been shown to be feasible and implementable on-line with a low computational burden. The results obtained in terms of localization of the objects and of the vehicle appear to be sufficiently accurate for navigation in the test environment, although they are corrupted by noise. Further improvements will consist in modifying the updating strategy in order to guarantee consistency of the global map over several iterations.

REFERENCES

Conte, G., S. M. Zanoli and L. Gambella (2006). On the problem of underwater simultaneous localization and mapping using mechanical scanning sonar. *Proceeding of the Second International Symposium on Communications, Control and Signal Processing*. Marrakech, Marocco.

Conte, G., S. M. Zanoli, L. Gambella and D. Scaradozzi (2006a). Acoustic Mapping and Localization of an ROV. *Proceedings 14th Mediterranean Conference on Control an Automation*. Ancona, Italy.

Dissanayake, G., P. Newman, H. F. Durrant-Whyte, S. Clark, and M. Csorba (2001). A solution to the simultaneous localization and map building (SLAM) problem. *IEEE Transactions on Robotic Automation*, **17**, pp 229-241.

Elfes, A. (1989). Using occupancy grids for mobile robot perception and navigation. *Computer*, **22,** pp 46-57.

Elfes, A. (1987). Sonar-based real-world mapping and navigation. *IEEE Journal of Robotics and Automation*, **3**, pp 249-265.

Gambella L. (2005). *Gestione di dati sonar per la navigazione autonoma*. Doctoral Dissertation. Università Politecnica delle Marche, Facoltà di Ingegneria. Ancona, Italy.

Gutmann, J.-S. and C. Schlegel (1996). Amos: a comparison of scan matching approaches for self-localization in indoor environments. *Proceedings of The 1st Euromicro Workshop on Advanced Mobile Robot*. Kaiserslautern, Germany.

Leonard, J. J. and H. F. Durrant-Whyte (1992). *Direct sonar sensing for mobile robot navigation*. Kluwer Academic Publisher.

Leonard, J. J., B. A. Moran, I. J. Cox, M. L. Miller (1995). Underwater Sonar Data Fusion Using an Efficient Multiple Hypothesis Algorithm. *Proceeding of the 1995 IEEE International Conference on Robotics and Automation.* Nagoya, Aichi, Japan.

Martin, M. C. and H. P. Moravec (1996). *Robot evidence grid.* The Robotics Institute, Carnegie Mellon University. Pittsburgh, PA.

Moravec, H. P. and A. Elfes (1984). High resolution maps from wide angle sonar. *Proceedings of the 1985 IEEE International Conference on Robotics and Automation*. St. Louis, Missouri, USA.

Newman, P. (1999). *On the structure and solution of SLAM building problem*. PhD thesis. Australian Centre for Field Robotics. Sydney, Australia.

Schiele, B. and J. L. Crowley (1994). A comparison of position estimation techniques using occupancy grids. *Proceedings of the 1994 IEEE International Conference on Robotics and Automation*, pp 1628-1634. San Diego, CA.

Schultz, A. C. and W. Adams (1998). Continuous localization using evidence grids. *Proceedings of the 1998 IEEE International Conference on Robotics and Automation*. Philadelphia, Pennsylvania, USA.

Tena Ruiz, I., Y. Petillot, D.M. Lane and C. Salson (2001). Feature Extraction and Data Association for AUV Concurrent Mapping and Localisation. *Proceedings of the 2001 IEEE International Conference on Robotics & Automation*. Seoul, Korea.

Thrun, S. (1998). Finding landmarks for mobile robot navigation. *Proceedings of the 1998 IEEE International Conference on Robotics and Automation*, pp. 958-963. Leuven, Belgium.

Williams, S., P. Newman, G. Dissanayake and H. Durrant-Whyte (2000). Autonomous Underwater Simultaneous Localisation and Map Building. *Proceedings of the 2000 IEEE International Conference on Robotics and Automation*, pp 1793-1798. San Francisco, CA.

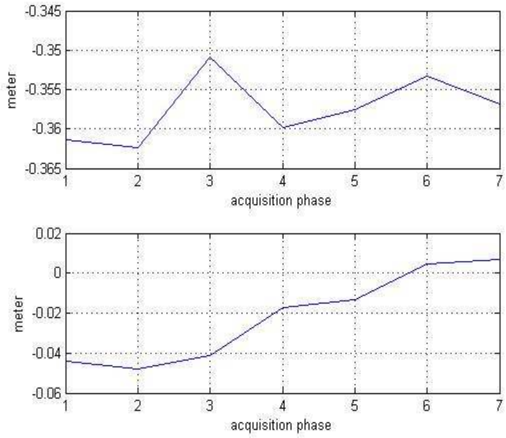

Figure 6. Error in the coordinates of object 1.

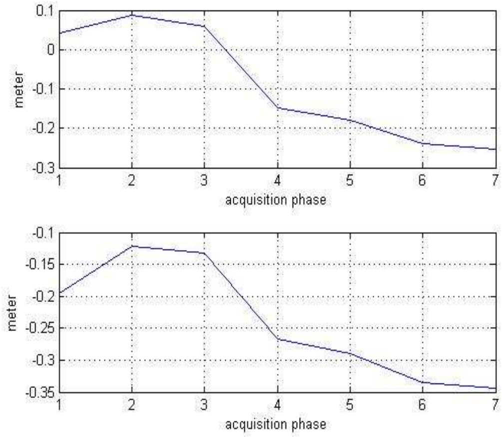

Figure 8. Error in the coordinates of object 3.

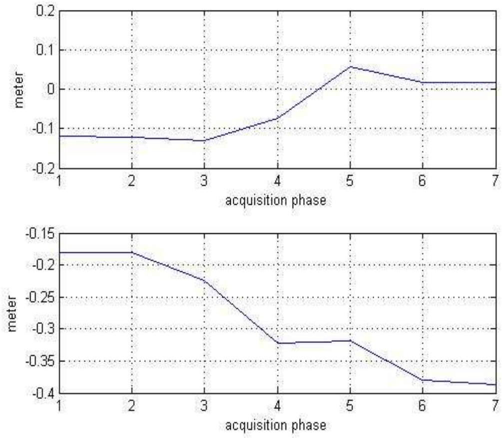

Figure 7. Error in the coordinates of object 2.

Table 1. Measured (x,y) position and estimated position of the ROV

acq. 1	0.53	0.9	0.53	0.90
acq. 2	0.47	1.11	0.53	1.15
acq. 3	0.49	1.27	0.48	1.4
acq. 4	0.82	1.21	0.63	1.3
acq. 5	1.05	1.21	0.58	1.15
acq. 6	1.26	1.11	0.88	1.15
acq. 7	1.33	1.36	0.83	1.21