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FOLAGA: A VERY LOW COST AUTONOMOUS UNDERWATER VEHICLE FOR COASTAL OCEANOGRAPHY

A.Alvarez*, A. Caffaz, A. Caiti***, G. Casalino***, E. Clerici**, F. Giorgi**, L. Gualdesi****, A. Turetta***, R. Viviani*****

** IMEDEA – Instituto Mediterraneo de Estudios Avanzados*
C/Miguel Marques 21, 07190 Esporlas, Spain
*** GRAALTECH s.r.l. – via Gropallo 4/10, 16122 Genova, Italy*
****ISME – Interuniversity Ctr. Integrated Systems for the Marine Environment*
c/o DIST, University of Genova, via Opera Pia 13, 16145 Genova, Italy
***** SACLANT Undersea Research Ctr., viale San Bartolomeo 400, 19138 La Spezia, Italy*

Abstract: .The Fòlaga second version, a very low cost prototypal AUV for coastal oceanographic purposes, is introduced. The vehicle has the mission of collecting oceanographic data over vertical ocean section at selected geographical points. For this reason, it can navigate on the sea surface, and dive only when measurements are needed. This behaviour is similar to that of aquatic birds that swim on the water surface and dive occasionally in search of food. The paper concentrates on the vehicle communication and mission planning modules, and on the analysis of field data to test the vehicle maneuvrability. *Copyright © 2005 IFAC*

Keywords: Autonomous vehicles, Marine Systems, Manoeuvrability, Man/Machine Interfaces.

1. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) are increasing their popularity in many marine operative fields, from oil industry to environmental research to military applications. However, they are still considered, and often are, expensive tools, difficult to be managed by an untrained user. Most AUVs have been designed in order to be able to fullfill many different missions, and to carry a great variety of payloads: in short, they have been designed as general purpose vehicles. This is in stark contrast with what can be observed in the field of AUV precursors, i.e., the Remotely Operated Vehicles (ROVs). Nowadays ROVs can be found in the market within a wide range of prices (starting at about € 20,000 and ending up 20 times more) and of design and configurations. Moreover, most ROVs can be used and maintained, after a very short training period (few days), by non-engineer end-users, as it is most often the case for instance in environmental organizations, or in civil service applications. In fact, the ROV developers, after a pioneering phase, have specialized the design of each ROV class toward specific end-users needs.

In this paper we report our on-going efforts in the design and evaluation of the *Fòlaga*, a prototypal AUV taylored to the needs of coastal oceanographic missions. The first vehicle version has been reported in (Alvarez et al., 2004b); here the second version of the vehicle is described, concentrating specifically on the mission planner and monitoring modules, and on the evaluation of manoeuvrability characteristics from data gathered at a field test site in Mallorca, Spain, on June 2004. The paper is organized as follows: in the next section some background on the Fòlaga design is given, including a brief review of related works. In section 3 the comunication and mission management software developed for the second version of the vehicle is described. In section 4 field data are reported, and data analysis procedures are described in order to evaluate some manoeuvrability characteristics of the vehicle. Finally some conclusions are given.

2. THE FOLAGA CONCEPT

Oceanographic observations of coastal areas have been traditionally carried out by oceanographic ships and moorings. Both systems, though, lack the required spatiotemporal resolution to cope with the fast, small scale, coastal ocean dynamics. For this reason different concepts of observing platforms have been investigated. These platforms include gliders (Stommel, 1989), and AUVs or AUV platoons (Schmidt et al., 1996; Bovio et al., 2004). Gliders are autonomous vehicles that exploit hydrodynamic shape and small fins to induce horizontal motions while controlling their buoyancy: changing buoyancy together with the hydrodynamic structure allow gliders to carry out zig-zag motions between the ocean surface and bottom with a net horizontal displacement. Gliders have been proved able to observe the interior of vast ocean areas over periods up to the scale of months. The employment of gliders to sample coastal areas is however quite limited, due to the strong energetic processes occurring in these environments. AUVs are ocean observing platform better suited to coastal areas. Their hydrodynamic shape, electrical propulsion, submarine navigation and positioning allows continuous sampling of oceanographic conditions. However, acquisition of AUVs is still prohibitive for many environmental agencies: as pointed out in (Gadre et al., 2003), the complexity and cost of deployement, in particular of platoons of AUVs, is a severe limiting factor to experimental activities. Programs for development of small, easy-to-operate, AUVs, have been succesfully developed (Allen et al., 1997), while the low cost of equipment and associated infrastructure, though claimed, has still to be attained. (Gadre et al., 2003) reports on the development of miniature AUVs for experimental purposes in which the part material cost has been effectively reduced, to reach a cost of less than $ 3000 in parts, with in-house development of most of the elctronics and mechanical components. The vehicle described in the present paper, the Fòlaga, has also been succesfull in limiting the part costs to a comparable figure (roughly € 8000, including payload) using exclusively commercially off-the-shelf (COTS) components.

The Fòlaga design has focused on the observation that a vehicle performing mesoscale ocean measures in shallow coastal waters has to exhibit a mixture of gliders and AUVs capabilities. In particular, it is allowed to navigate on the surface for most of the time, and it has to dive, possibly vertically, at the selected measurement locations. In nature, this behaviour is similar to those of several aquatic birds; one of these is the *fòlaga*[1], a bird leaving in marsh, lagoons and coastal areas, swimming mostly on the water surface and occasionally diving at shallow depths in search of food. The robotic version of the Fòlaga does not attempt to capture the bird shape, but its behaviour: it navigates on the sea surface, with GPS and compass; it dives at selected positions down to 100 maximum depth (effective diving depth at each position is selected by the user, and monitored by the system through a depthmeter). The Fòlaga carries a CTD (conductivity, temperature, depth) sensor as payload, and, when on surface, it maintains contact with a surface station through a GSM telephone link. The link is used to transmit the current vehicle position and the oceanographic data (once re-surfaced). It can be used from the surface station to reprogram on-line the vehicle mission or for remote control by acting directly on the vehicle propulsors. In this last case, the Fòlaga is turned into an untethered remotely controlled vehicle.

Some of the technical carachteristics of the Fòlaga, described in (Alvarez et al., 2004b), are here briefly summarized for completeness. The vehicle is composed by two cylindrical fiberglass sections, connected at the center, for a total length of about 3m, and 0,12m diameter. The two-sections design allows for easy transportation, while the resulting elongated and thin shape, together with two vertical fins located at stern and bow, guarantees good track-keeping performance. Inside the cylinders, the electronic package and the battery power packages are hosted. The Fòlaga is powered by lead acid batteries guaranteeing 8 hours of autonomy. The propulsion is obtained through jet flow pumps. The second vehicle version has six pumps, two for horizontal propulsion (at the stern), two for vertical propulsion (at bow and stern respectively) and two lateral propulsors for steering purpose, located at the vehicle bow, that allow the vehicle to turn even at zero surge velocity. The two vehicle versions are depicted in Fig. 1. In Fig. 2 some details of the vehicle assembly (second version) are shown.

Vehicle control and navigation have been implemented accordingly to the general approach introduced in (Aicardi et al., 1995) and specialized to the underwater environment in (Aicardi et al., 2001a; Aicardi et al., 2001b); it has been thoroughly described in (Alvarez et al., 2004b). The first vehicle version and data from its test trials in spring 2003 have also been reported in (Alvarez et al., 2004b). Following that experience, a second version has been designed, on behalf ot the oceanographic institution IMEDEA, to which it has been given on June 2004. For this second version, a GIS-based mission planner and monitoring system has been developed, and it is described in detail in the next section together with the overall system communication procedures.

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[1]*Fòlaga* is the Italian name; the same bird has the somehow less inspiring English name *coot*

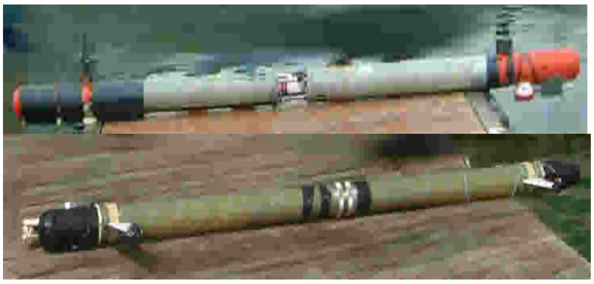

Fig. 1. The first (top) and second (bottom) version of the Fòlaga. The main difference between the two versions is in the vertical propulsion pumps: in the first version there is one pump placed at the center of the vehicle, in the second version there are two pumps placed at the bow and stern of the vehicle respectively.

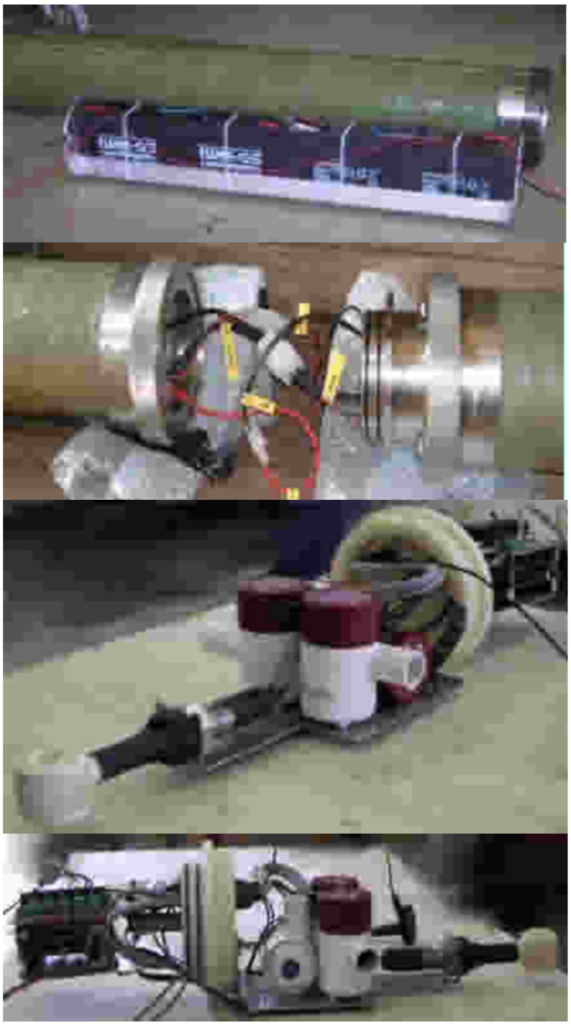

Fig. 2. Some realization details of the Fòlaga, second version. From top to bottom: mid section with battery pack lodging; central section, with mechanical, electrical and electronic connections; bow end-cap, wet side, with CTD sensor (the "nose"), and the two steering lateral jet pumps; again bow end-cap, side view, with the CTD, the lateral steering pumps and the vertical diving pump visible on the wet side (right), and the electronic package on the dry side (left). The connections trhough the cap between wet and dry sides have been coiled with epoxy.

3. SYSTEM COMMUNICATION PROCEDURES AND MISSION MANAGEMENT

Communication exchanges among the system components are implemented through TCP/IP procedures. In particular, communications take place between the vehicle and the user interfaces on the surface station. On the surface station there are two different interfaces: one is the *system engineer* interface, which gives information on the vehicle current state: measured geographical position and orientation, propulsor commands, alarm state, GSM link monitor, mission setting (next desired location) and allow, when the Fòlaga works on open loop, to teleguide it sending direct control to the engines/propulsor. The system engineer interface module receives the data from the AUV by a GSM link, stores them in an incrementally log file and also communicate them to the *oceanographic mission manager* interface, which will be described later on in this section. After vehicle diving, when communication is re-established, the system engineers interface receives the oceanographic data (conductivity and temperature as a function of depth), stores them on hard drive and pass them to the mission manager by LAN. The overall communication topology is depicted in Fig. 3. It may be interesting to note that the oceanographic mission manager receives data only from the system engineer interface. It may be also of interest the design choice of operating system: the vehicle on-board computer runs under the Linux system, while both the surface station interfaces runs under Windows XP. The latter choice has been motivated by the desire of having the vehicle interfaces easily installable on the most diffused operating system for portable computers and making its use easier at the same time. While an embedded system based on Lynux has been realized on the vehicle, as this operating system proved to be more robust and flexible in managing communication procedures by GSM. The mission manager has been designed as an high-level interface for the oceanographer end-user to plan a vehicle mission,

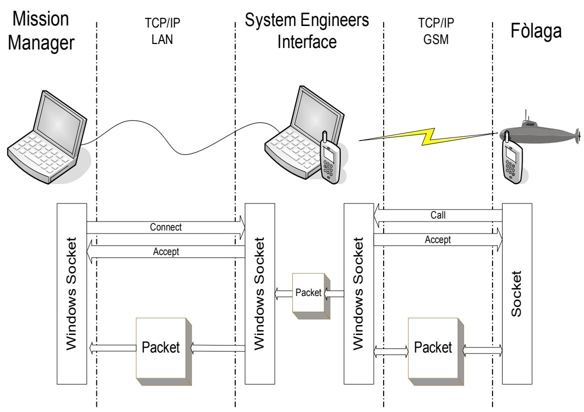

Fig. 3. The communication scheme implemented among the various system components. The vehicle exchange data with a system engineer interface (vehicle control interface); the system engineer interface exchange data with the oceanographic mission manager interface. All communications take place through TCP/IP.

monitor the vehicle trajectory under navigation, display the oceanographic data as they become available after a measurement, play back navigation and oceanographic data. In order to fulfill these tasks in an intuitive way for the users, the mission manager has been built through a Geographically Information System (GIS), that is, as a geographically referenced data base. In particular, a mission can be planned by defining over the displayed geographical chart via-points and mission points, including requested diving depths. The GIS interface can display additional prior information relevant to the mission, as for instance bathymetry. Mission editing, saving, etc. are also available features. An example of the mission planner interface is in Fig. 4. The planned mission is downloaded to the vehicle system through the system engineer interface link. Once a mission is started, the navigation data from the vehicle are displayed by the mission manager over the same geographical charting information, and also over the planned via points and measurement points. An example of mission monitoring, from field test data, is shown in Fig. 5. In Fig. 5 there are at least two additional features interesting to note beyond the GIS-based interface, and that are typical of the Fòlaga behaviour. The first is that the planned via points are reached not necessarily through straight lines, but through smooth and well-behaved routes, as expected from the navigation algorithm of (Aicardi et al., 1995, 2001a, 2001b). The second interesting feature is related to the loops around the via points reached by the vehicle: with the Fòlaga actuators it is rather straightforward to show that the vehicle position is asymptotically stable, but not the orientation. So the vehicle can reach the desired via point, but with orientation influenced by the sea and

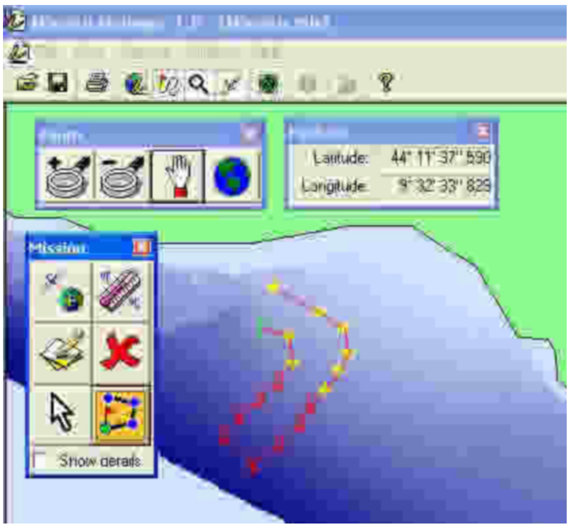

Fig. 4. Mission planner panel of the oceanographic mission manager. The user can indicate desired vehicle via-point (stars) and measurement points over a geographical chart displaying also the working area bathymetry (or other information as needed). Insertion of points directly through geographical coordinates or as range and bearings from the current position is also possible.

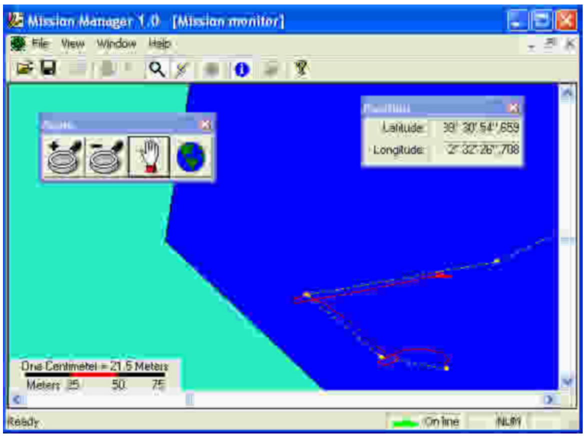

Fig. 5. Mission monitoring panel of the oceanographic mission manager. The current vehicle position is displayed, together with the past vehicle trajectory, the desired via-points (connected through straight lines) and the geographical charting layer. Field data from June 2004 field test in Cala Major.

wind conditions, or other external disturbances. The data displayed in Fig. 5 have been collected at a field test performed at the IMEDEA sites in Cala Nueva and Cala Major, Mallorca, Spain, in June 2004. In the next section, some additional data from this tests are presented and discussed in order to estimate some manoeuvrability characteristics of the vehicle.

4. VEHICLE MANOEUVRABILITY FROM EXPERIMENTAL DATA

In this section we report data from the vehicle surface navigation acquired with the purpose of estimating the Fòlaga speed at full propulsion power, and the curvature radius at full speed. To this aim, the Fòlaga was in teleoperation mode, and was steered through the following manoeuver: with full propulsion power, the vehicle rudder has been kept in succession, at three minutes interval, at midship, full left, midship, full right, midship, full right, midship full left. Note that in this case the vehicle navigates in open loop. Of course, in the Fòlaga case, the rudder action is obtained through the steering pumps. GPS data were collected by the vehicle during the operation, at 1 Hz sampling. The measured vehicle trajectory is reported in Fig. 6, where the numbered sections indicate the portions of the trajectory in which the rudder was at midship, i.e, the sections that, in absence of perturbation, should correspond to straight lines. It is clear from the navigation data that during the test there was a non-negligible effect of external perturbations. This has made necessary the estimation of such external disturbances. They will be in the following referred as "currents", since this is considered the most likely perturbation effect in the area. However, in general, perturbations may also be due to the combined action of other environmental effects, as wind, wave motions, etc.

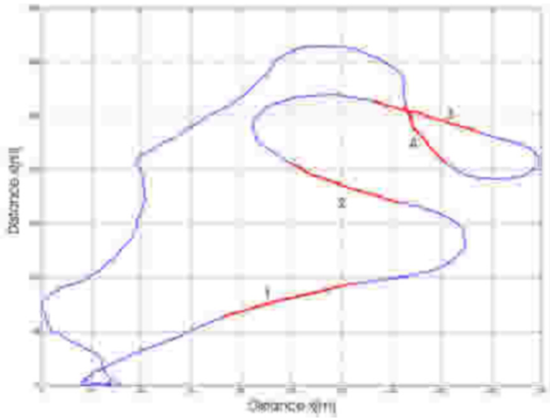

Fig. 6. Fòlaga GPS-measured navigation during the maneuverabilty test. Numbered sections indicate the trajectory portions with midship rudder.

In order to estimate the current effect, a kinematic model is employed, with a reference system as illustrated in Fig. 7. In the following, u is the unknown vehicle surge speed, $\mathbf{v}$ is the vehicle measured velocity (from GPS navigation data), $\mathbf{c}$ is the unknown current perturbation. The compass reading gives, with the same GPS sampling, the measurement of the angle $\sigma(t)$. The relation among u, $\mathbf{v}$ and $\mathbf{c}$ at any time instant is:

$$\begin{bmatrix} 1 & 0 & \cos(\sigma(t)) \\ 0 & 1 & \sin(\sigma(t)) \end{bmatrix} \begin{bmatrix} c_x(t) \\ c_y(t) \\ u \end{bmatrix} = \begin{bmatrix} v_x(t) \\ v_y(t) \end{bmatrix}. \quad (1)$$

It is well known hat exclusively knowing the GPS data on position, and the vehicle not having a sensor for measuring the Surge velocity relative to the water, we can not univocally determine the speed of the current and the vehicle, as there are infinite combinations that can satisfy the equations system (1) at every instant. However, assuming the surge speed u and the current speed $\mathbf{c}$ as constant along the portion of trajectory where the rudder was held at midship, hypothesis compatible with the environmental properties, a least square system in the three unknowns c_x, c_y, u can be built for each trajectory segment:

$$\mathbf{\Sigma} \begin{bmatrix} c_x \\ c_y \\ u \end{bmatrix} = \mathbf{V} \quad (2)$$

where the matrices $\mathbf{\Sigma}$ and $\mathbf{V}$ are built as follows:

$$\mathbf{\Sigma} = \begin{bmatrix} 1 & 0 & \cos(\sigma(t_1)) \\ 0 & 1 & \sin(\sigma(t_1)) \\ 1 & 0 & \cos(\sigma(t_2)) \\ 0 & 1 & \sin(\sigma(t_2)) \\ \ldots & \ldots & \ldots \end{bmatrix} \qquad \mathbf{V} = \begin{bmatrix} v_x(t_1) \\ v_y(t_1) \\ v_x(t_2) \\ v_y(t_2) \\ \ldots \end{bmatrix} \quad (3)$$

The most critical part in these procedure has been the estimate of the values in $\mathbf{V}$. In fact, the vehicle velocity has been estimated from finite differences of the GPS position data, and subsequent low pass and moving average filtering.

The results obtained as for the estimate of the current effects are reported in Fig. 8. It can be seen that the estimated current vector exhibits some spatial variability; this is compatible with a current following the coast line, since the sea trial took place in a gulf (see Fig. 5 for a crude approximation of part of the coast line in Cala Major). Once the current velocity has been taken itno account, the average vehicle speed estimated from all the trajectory portions analyzed is $u = 0.4$ m/s, i.e.,slightly less than 1 knot.

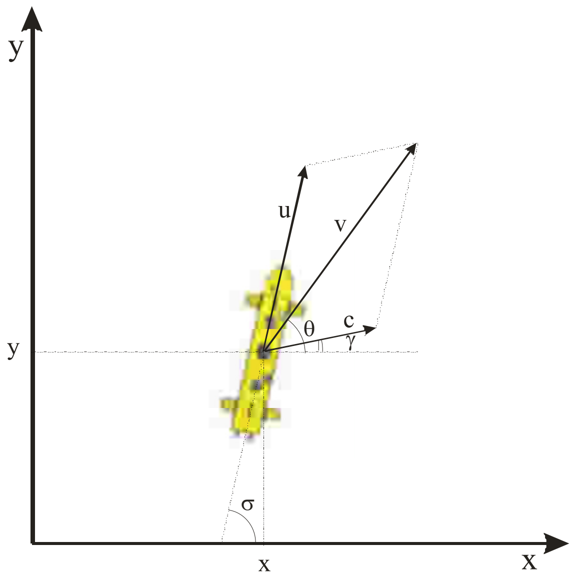

Fig. 7. Reference system for estimation of the current perturbation $\mathbf{c}$ and vehicle surge speed u.

The estimated current field has been employed also in the turning portions of the trajectory in order to estimate the vehicle turning radius at full speed. Let $\mathbf{s}(t)$ be the position of the vehicle at time t. Then:

$$\mathbf{s}(t) = \int_0^t \mathbf{v}(\tau)d\tau = \mathbf{s_0}(t) + \int_0^t \mathbf{c}(\tau)d\tau \quad (4)$$

where $\mathbf{s_0}$ is the vehicle position without the current effects (nominal trajectory). Reminding that we are assuming a constant current during the turnings, then the curve $\mathbf{s_0}(t)$ can be estimated from the data and from the previous current estimate through equation (4). This has led in particular to the determination of the nominal turning trajectories of Fig. 9. Vehicle turning radius has been estimated by fitting a circumference to both nominal trajectories, and taking the average of both estimated radii. The final estimate of the vehicle turning radius at full speed is $r = 23.8$ m.

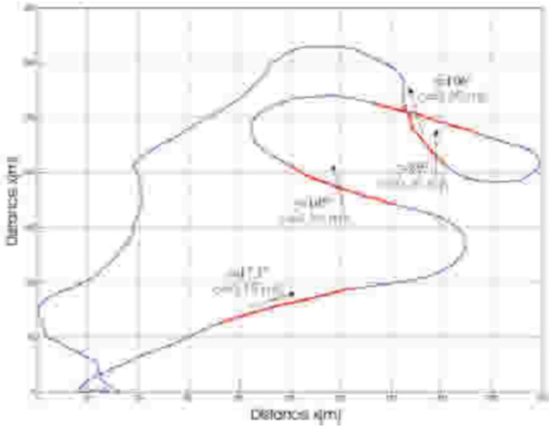

Fig. 8. Estimated current field (modulus and orientation).

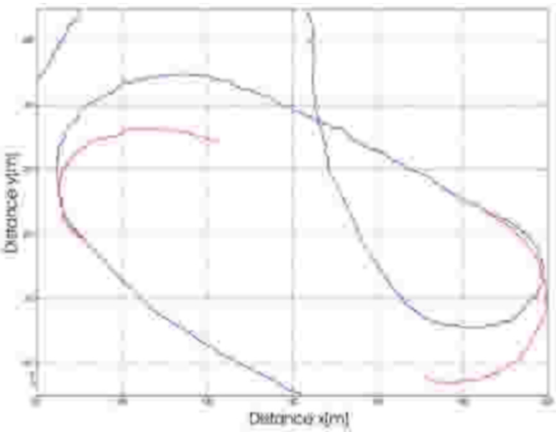

Fig. 9. Effective vehicle trajectory (dark blue) and nominal turning trajectory (light red) after correction for current effects.

5. CONCLUSIONS

The Fòlaga concept, its specific design and realization, the communication and mission planning software, and the monitoring software available on the second prototypal version have been described. Field data have been presented to evaluate some manoeuvrability characteristics of the vehicle. The results obtained evidentiate a relatively large turning radius at full speed r, and a relatively low maximum reacheable velocity u. This last factor, in particular, may create problems in situations in which the current speed may be close or higher than 1 knot. In these situations, the mission planning phase should be conducted exploiting any available prior knowledge on the current field, and using the environmentally optimal path planning method introduced in (Alvarez et al., 2004a).

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