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ACOUSTIC COMMUNICATION AND LOCALIZATION IN AUV COOPERATIVE SURVEYS

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Abstract: *The experimental results in acoustic communication and localization obtained with the “Typhoon” Autonomous Underwater Vehicle (AUV) in the CommsNet13 field trial are presented. The “Typhoon”s are a set of three AUVs developed by the Authors within the framework of the “Thesaurus” project, funded by the Tuscany Region, aiming at developing techniques for systematic cooperative autonomous exploration of marine archaeological areas by AUVs. The CommsNet13 experiment, which took place in September 2013 in the La Spezia Gulf, North Tyrrhenian Sea, was organized and scientifically coordinated by the NATO S&T Org. Ctr. for Maritime Research and Experimentation (CMRE); it included among its objectives the evaluation of on-board acoustic Ultra-Short Base Line (USBL) systems for navigation and localization of AUVs.*

Keywords: *Autonomous Underwater Vehicles; Acoustic Communication; Distributed Sensor Networks*

1. INTRODUCTION

The potential of Autonomous Underwater Vehicles (AUVs) working as a team in sampling, monitoring and surveillance has been realized since quite a long time [1]. However, the autonomous operation of a team of AUVs, with distributed decision capabilities, is still in the experimental research phase. The most relevant obstacles to the operational implementation of the concept reside in the limitations of the acoustic channel for inter-vehicle communications, and in the uncertainties in underwater navigation associated to the use of tactical grade Inertial Navigation Systems (INS). The latter is often used on board of AUVs in order to limit the vehicles cost; however, the typical horizontal navigation error drift from a tactical grade AUV can be of several thousand meters per hour [2]. Most AUVs employ Doppler Velocity Loggers (DVLs) as auxiliary sensors in order to increase the time window of reliability of dead reckoning navigation, but in the final end, even with DVLs, the navigation error drift requires a re-setting of the absolute position through re-surfacing and acquisition of a Global Positioning System (GPS) fix, at the very best after few (2-3) hours of underwater operation.

As for navigation accuracy, there are alternatives to the resurfacing and GPS fixing procedure: the first commercial AUV, the Hugin, used the HiPap Ultra Short Base Line (USBL) acoustic positioning system operated from an ancillary ship, and the acoustically estimated position was then communicated to the vehicle thanks to the acoustic modem capabilities of the HiPap transducers [3]. Another alternative is represented by the use of Long Base Line (LBL) acoustic positioning systems [4]. These acoustic positioning techniques have been designed for single-vehicle operations. However, whenever a team of AUVs is considered for search/surveillance/survey missions over wide areas, the use of auxiliary ship(s) is indeed a strong limitation for the team autonomy, and ultimately limits the cost efficiency of the AUVs operation. The use of a LBL system requires the a priori definition of the survey area, which may or may not be an option for the mission at hand.

Motivated by the task of archaeological relict search over extended areas, our research group has been developing techniques for acoustic communication and cooperative localization for AUV teams, based on the commercial availability of acoustic modems with USBL capabilities at affordable costs. The basic idea is to use a USBL-capable vehicle at the sea surface, i.e., with GPS availability, to localize and georeference the submerged members of the team. The georeferenced position is then communicated acoustically to the submerged vehicles, and exploited as an alternative to GPS fixes. Note that, in order to cooperate toward the mission goal, the AUVs need also to communicate among themselves information regarding the mission status [5], [6]. An architecture for concurrent cooperative communication and localization has been presented by our group [7], [8] in the framework of the “Thesaurus” project [9]. In any system considering concurrent communication and localization, it has to be carefully evaluated the trade-off between the two concurrent tasks: in particular, communication in the team is achievable through some networking structure; the network structure in turn implies an overhead that results in communication delays (in addition to those traditionally experienced and due the physical characteristics of the underwater acoustic channel). Are the acoustic fixes communicated at a fast enough rate to avoid unacceptable drifts in the AUVs navigation? In this paper we report some experimental results to help to evaluate the performance trade-off at least in the case of our own developed communication/localization system. The data have been gathered within the CommsNet 13 cruise, organized by the NATO

Centre for Maritime Research and Experimentation (CMRE) in September 2013, and taking place in the waters of the Gulf of La Spezia, Italy, North Tyrrhenian Sea.

The paper is organized as follows: in the next section the communication/localization scheme proposed in [7], [8] is briefly reviewed, for self-consistency, but omitting the implementation and algorithmic details that have already been reported in the cited works. In Section 3 the experiment set-up is described. In Section 4 the localization and underwater navigation results are presented. Finally, conclusions are given.

2. CONCURRENT ACOUSTIC COMMUNICATION AND LOCALIZATION

The communication/localization algorithms of the “Thesaurus” project [7], [8] have been implemented on the project-designed vehicles, the “Typhoon” AUVs, Fig. 1. Three Typhoons have been built within Thesaurus, differing from each other in terms of payload instrumentation and communication equipment. In particular, as for the communication aspect which is of interest here, one vehicle is equipped with a USBL-capable modem, while the other two are equipped with standard modems [10].

The vehicles establish a communication network based on a time-sharing bi-directional/broadcast communication scheme. We have opted for a Time Division Multiple Access (TDMA) broadcast messaging scheme, with no multi-hop (hence routing) capability. In the implemented network architecture, the bottom layer is represented by acoustic modem/USBL, which manages the physical transmission of the signals. The modem also implements collision avoidance techniques (Medium Access Control - MAC) and provides basic network functionalities, including an addressing system that can be exploited at the link layer.

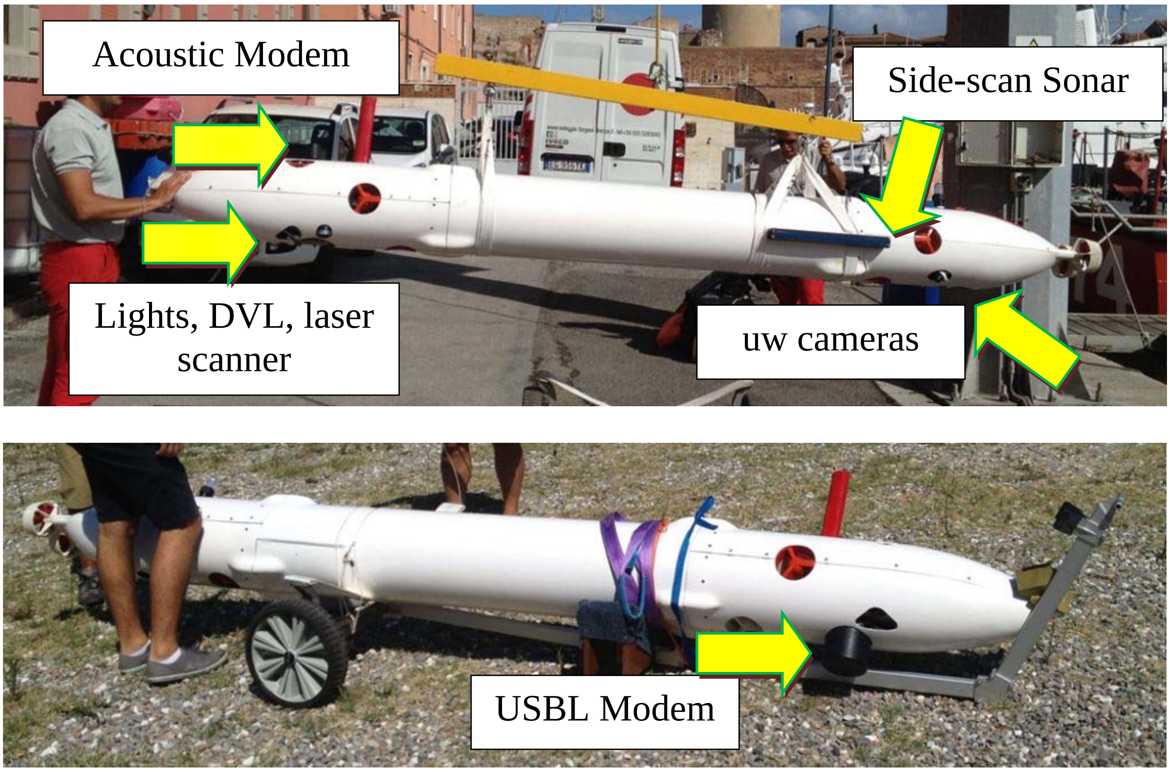

Fig. 1: two of the three Typhoon vehicles – the top one with standard acoustic modem and payloads for underwater search, the bottom one with USBL modem

The medium access control is completed through a time division mechanism: time is divided into windows and each node/vehicle is assigned a time slot where it has to concentrate all its communication burden. The on-board data from the INS (in the Typhoon case consisting in X-Sense Inertial Measurement Unit) are fused with all possible other sources of information, i.e., ground velocity from DVL (if available), GPS data (when on surface), acoustic ranges (determined from message exchanges), georeferenced position messages (as received form the USBL vehicle). The fusion algorithm is a version of the Extended Kalman Filter (EKF) that takes care of the difference in rate of the various information, and in particular that the information from the communication system, either range only or complete geolocalization, arrives asynchronously with respect to the other sensors, and also at irregular intervals, due to the delay in transmission and the disturbances in the channel, including occasion fading.

3. EXPERIMENTAL SET-UP

The CommsNet 13 experiment has been organized by CMRE with the main objective to test the performance of several acoustic communication and localization systems using underwater networks. Several teams from different institutions, each one interested in testing different systems, have been involved in the experimentations, held with the support of NRV Alliance. All the teams were using Evologics modems, to guarantee compatibility at the physical level. A complete description of the activities of the Thesaurus project team within CommnsNet 13 cruise is being reported in [11]. Here we report on the data (communication and navigation) gathered with the USBL-equipped Typhoon (bottom of Fig. 1). The test with the Typhoon AUV consisted in:

- deploying some (5 in our case) modems at the sea bottom, in unknown location;
- with the USBL AUV at the sea surface (i.e., with GPS contact), gather position data from the bottom-moored modems, in order to georeference them;
- use the georeferenced bottom-moored modems to get acoustic fixes through communication with USBL modem;
- integrate the acoustic fixes with the on-board INS data (the USBL AUV does not have a DVL sensor).

The experiment is done with the USBL vehicle at the surface, in order to have GPS as ground truth data. Moreover, the EKF is initialized using GPS data as well, in order to avoid initial conditions problem. Note that the acoustic localization data are obtained using the TDMA communication protocol, so that every modem is interrogated in a round robin fashion. The localization system is a hybrid between classic LBL and USBL methods: indeed, the vehicle is using a USBL sensor over a net of LBL nodes.

The experiment took place within the La Spezia harbor, in very shallow water (4 to 16 m depth), with horizontal distance between the various communicating nodes always less than 1000m (Fig. 2). The measured sound speed profile at the time of the experiment was constant with depth (1533 m/s, water temperature 23 °C, salinity 38.08 psu) in the early morning, gradually developing a downward reflecting gradient during the day. Sea state was 0 in the morning, with a gentle breeze developing in the afternoon and leading to sea state 1 – 2. The modems (both standard and USBL) operate with approximately 8 KHz bandwidth, centered around 30 KHz [10].

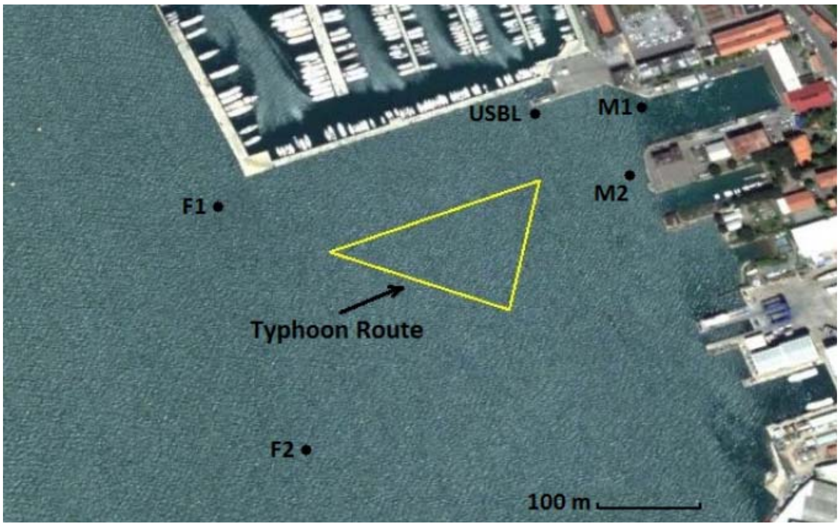

Fig. 2: experimental configuration for the CommsNet13 exercise reported. The black dots indicate the seabed modem nominal positions; the yellow triangle the nominal route of the USBL Typhoon. Note that one of the bottom-moored modem is a USBL modem, used as a standard one.

4. RESULTS

Bottom-moored modems georeferentiation is reported first. In Fig. 3 the clusters of individual acoustic fix from each of the bottom-moored nodes are reported, for both the morning and the afternoon of the experiment day. Note that both in the morning and afternoon outliers are present from modem M1. In the afternoon, possibly because of the downward reflecting gradient, there was no communication with modem F2 and just one fix for F1. After outlier removal, the clustered acoustic fixes from each modem have been averaged, in order to get a mean georeferenced position, and the standard deviation computed and reported in Table 1. Note that the uncertainty in the georeferentiation is caused by the inherent uncertainty in the USBL fix, by the motion of the moored modems, and by the GPS error.

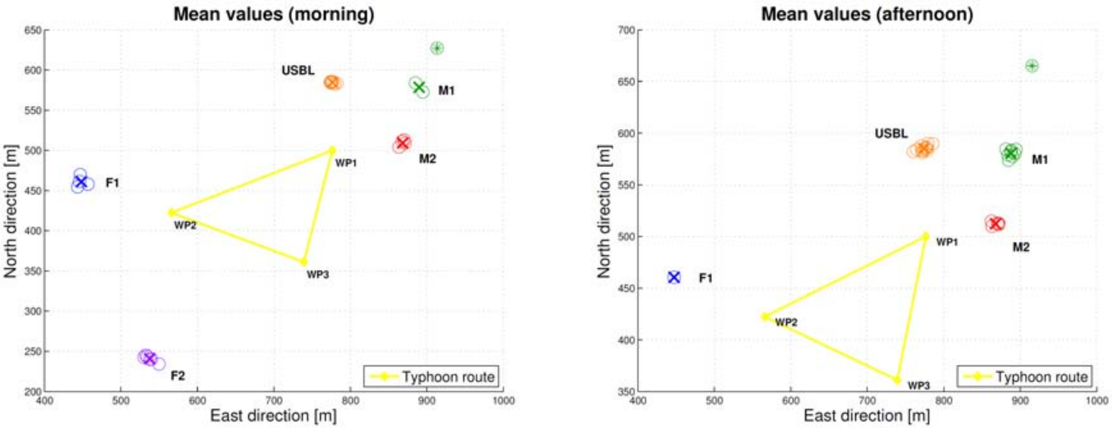

Fig. 3: estimated position (dots) and mean value (cross) of the bottom moored modems from the surface measurement of the USBL Typhoon, in the morning (left) and in the afternoon of the experiment day.

Bottom-moored modem identifier	Standard deviation of position estimate (m)	
	morning	*afternoon*
M1	0.8	4.2
M2	4.1	3.7
USBL	2.0	6.4
F1	5.2	-
F2	4.5	-

Table 1: standard deviation in bottom-moored modem absolute georeferentiation

The runs with the USBL Typhoon navigating at the surface, which are relevant for this paper, have taken place in the morning. In Fig. 4 the Typhoon repeated paths above the nominal trajectory are shown, together with the acoustic fixes from USBL and the GPS ground truth at the time of the acoustic fix reception. In Table 2 the numerical values of the discrepancy between acoustic fixes and GPS positions are reported. Note that these discrepancies are all inside the "3σ" rule, i.e., less than three times the standard deviation of the position estimates (Table 1), however, they are visiting the boundaries relatively often. Fig. 5 reports the estimated trajectory with the EKF. Note that the EKF is initialized using also the GPS signal, then GPS is switched off from the EKF input. Fig. 6 reports the error between the EKF estimate and the GPS ground truth, together with the time instants in which an acoustic fix is received. One can observe that indeed the EKF navigation has a relevant drift when only INS data are used, and that the acoustic fixes are sufficient at beating the error down to acceptable levels. The acoustic fixes come with quite large intervals, due to the communication scheme behind their transmission: often packets are lost (between 30% and 70% packet loss was experienced), and the round robin scheme implies a delay that is proportional to the number of nodes. The largest error in the data (~ 40m) is registered in correspondence of the largest interval between two consecutive acoustic fixes (~ 3 minutes). Note that, if only localization is the issue, the modems can operate as pingers at a much faster rate. However, if communication is interleaved with the localization process, the transmission delays reported here are much closer to those that could be experienced in a team operation. Finally, conclusions are given.

5. CONCLUSIONS

The results in terms of localization accuracy of a concurrent communication and localization acoustic scheme for application in the operation of AUV teams for distributed search, survey and surveillance, have been presented. The data reported show how acoustic fixes obtained from the communication process are indeed successful in limiting the drift of on-board INS navigation system. However, the concurrence of communication and localization, at least in our current implementation, coupled with the fluctuations of the acoustic channel, causes large intervals between consecutive acoustic fixes.

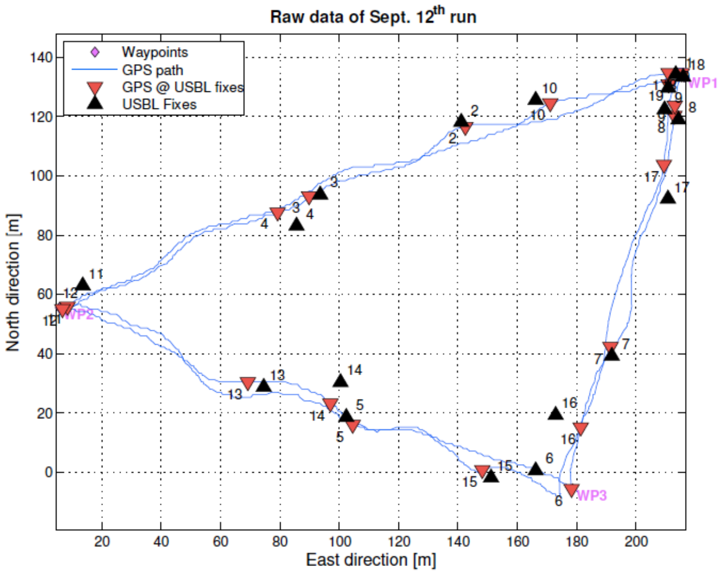

Fig. 4: Typhoon path from GPS data (thin blue line), acoustic fixes from the on-board USBL (black upward triangles), corresponding GPS position (red downward triangles)

Fix #	Error (m)	Fix #	Error (m)	Fix #	Error (m)
1	2.3	7	1.9	13	8.4
2	3.4	8	3.1	14	4.3
3	8.2	9	5.1	15	9.8
4	3.0	10	8.5	16	11.6
5	13.2	11	2.1	17	1.3
6	2.9	12	5.9	18	1.2

Table 2: discrepancy between the GPS measured positions and the acoustic fixes

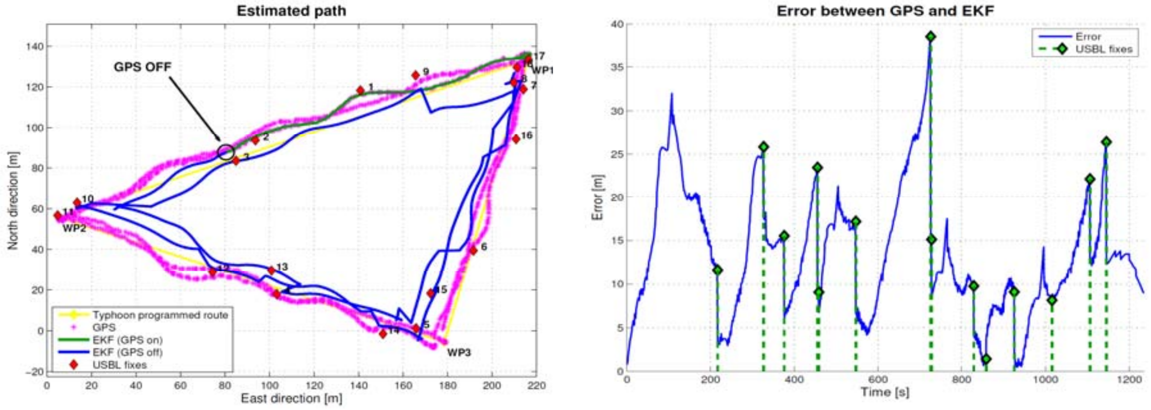

Fig. 5: Left: GPS measured path (thick purple line), EKF estimated path (thin blue line), acoustic fixes (red diamonds); Right: discrepancy as a function of mission time between the GPS measurements and the EKF estimate, shown for a 20 minutes time window; the green diamonds correspond to the time instants in which an acoustic fix is received. The acoustic fixes succeed in beating down to zero the otherwise increasing drift in horizontal position estimate with INS only

6. ACKNOWLEDGEMENTS

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