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Fenucci, D., Caiti, A., Simetti, E., & Casalino, G. (2016, August). Underwater communication requirements in coordinated autonomous manipulation: The MARIS project. In Underwater Communications and Networking Conference (UComms), 2016 IEEE Third (pp. 1-5). IEEE.

The final authenticated version is available online at:
https://doi.org/10.1109/UComms.2016.7583468

You are welcome to cite this work using the following bibliographic information:

BibTeX

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@INPROCEEDINGS{Fenucci2016underwater,
  author={D. Fenucci and A. Caiti and E. Simetti and G. Casalino},
  booktitle={2016 IEEE Third Underwater Communications and Networking
      Conference (UComms)},
  title={Underwater communication requirements in coordinated
     autonomous manipulation: The MARIS project},
  year={2016},
  pages={1-5},
  doi={10.1109/UComms.2016.7583468},
  month={Aug}
}
```

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Underwater Communication Requirements in Coordinated Autonomous Manipulation: the MARIS Project

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***Abstract*—This paper addresses the communication requirements needed within the MARIS project, which involves several Italian institutions. The goal of the MARIS project is to develop technologies for autonomous underwater interventions, in particular to enable two floating manipulators in executing joint grasping and transportation activities. In this context, communication issues are mainly related to the information exchange needed by the cooperation algorithms during all the phases of the mission, in particular in the coordinated transportation. Simulation results show the expected performances of the cooperative algorithm as the communication rate changes. Based on these results, a strategy to meet the requirements imposed by the cooperation and to achieve the mission objective with the available devices is presented.**

I. Introduction

The growing need for autonomy in situations where human intervention could be impractical, costly or too dangerous has led to significant developments in autonomous robotics. In the underwater domain, starting from the Autonomous Oceanographic Sampling Network (AOSN) concept [1], the research efforts have been focused on Autonomous Underwater Vehicles (AUVs). Teams of multiple, cooperative AUVs are becoming now a suitable tool to be employed in a wide range of typical marine applications, such as seabed exploration and mapping, environmental monitoring and harbour patrolling.

Some recent catastrophic accidents, such as the Deepwater Horizon explosion in the Gulf of Mexico or the Fukushima nuclear disaster, have pointed the attention on Autonomous Underwater Intervention (AUI). AUI is another relevant field of underwater robotics, which deals mainly with grasping, manipulation and transportation activities. The need of smart underwater robots has emerged not only for interventions in extremely hostile environmental conditions, but also for civil and military routine operations, i.e. de-mining or infrastructure maintenance in off-shore industry. The promising results of some pioneering [2], [3] and more recent [4], [5] research projects have encouraged to explore new challenges in the AUI field. The Italian national project MARIS (Marine Robotics for Interventions) [6], funded by MIUR (the Italian Ministry of Education, University and Research), aims to enable cooperation among autonomous underwater intervention robots for joint dexterous manipulation operations and transportation activities.

Underwater communication clearly plays a crucial role to enable cooperation among vehicles. The well known limitations of the acoustic channel in terms of bandwidth, communication delays and latency [7] may indeed affect the performance, robustness and even the stability of the overall system. Underwater optical transmissions may overcome the tight constraints imposed by the acoustics at ranges of few meters, but may suffer from other operational constraints in the AUI scenario, as occlusions, sensitivity to turbidity and, in shallow waters, to daylight changes [8].

Communication requirements are strictly dependent on the specific application or even on the single task to perform. Usually, the more critical a task for the stability of the distributed system, the higher the information exchange rate required among the agents. From a qualitative point of view, tactical information of useful semantic significance, not intended to be used in a control loop but for mission supervision only, can be transmitted even every tens of seconds of even minutes [9], [10]. On the other hand, acoustic positioning informations for navigation [11] or formation control [12] purposes are typically delivered at a frequency of $0.1 - 1$ Hz, and even higher communication rates can be necessary for more delicate tasks, such as the coordinate motion planned for the MARIS project described in the next section.

In this paper, communication requirements needed by the cooperative autonomous grasping and transportation tasks developed within the MARIS project are addressed, and possible communication strategies to ensure the success of the cooperative mission are briefly analysed.

II. The MARIS project

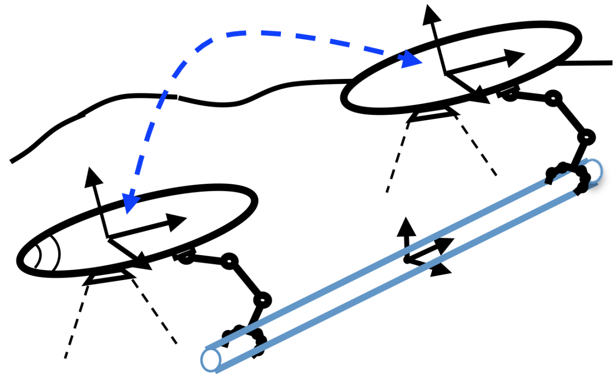
The MARIS project aims at further developing and integrating technologies and methodologies to enable the realization of cooperating autonomous robotics systems for underwater manipulation and coordinated transportation activities. More specifically, the general objective of the project is to investigate the possibility of using a couple of underwater floating manipulators to perform the coordinated manipulation and/or transportation of a common object which can not be handled by a single agent.

In such a scenario, the autonomous cooperative mission can be divided in three sequential phases:

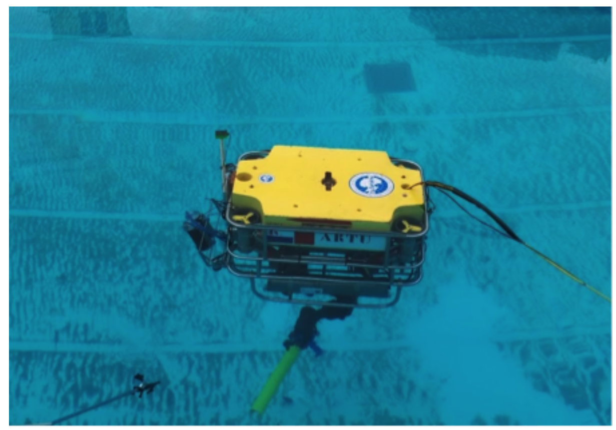
- *Navigation*: the two vehicles travel from their respective starting point to the object location, exploiting the on-board Inertial Navigation System (INS) and the other aiding sensors, e.g. Doppler Velocity Log (DVL), or acoustic beacons in known positions, to compute their navigation status.
- *Grasping*: each floating manipulator grasps the object in two different points with respect to a common reference system fixed to the object.
- *Transportation*: the vehicles transport in a coordinate way the grasped object in a predefined area.

It is assumed that each vehicle is equipped with an on-board acoustic modem with Ultra-Short Base Line (USBL) capabilities. Such modem is used to: exchange messages among the vehicles; allow mutual relative localization of the two vehicles; and, when in presence of external acoustic beacons or transponders, anchored in known positions, acquire absolute position information. Cooperation among the vehicles takes place at different levels of intensity, progressively increasing in the various mission stages. During the initial phase, cooperation is directed mainly to the mutual localisation of the vehicles, so that they can jointly proceed toward the object to be grasped and transported. As the agents approach the object and start working close each other, cooperation is necessary in a stronger way to complete the coordinate grasp of the object, exchanging at the end their respective gripping position with respect to the common object-fixed reference frame. Coordination becomes critical in the final part of the mission, represented in Fig. 1a, when the vehicles must be able to navigate while also avoiding to collide and grasping the shared object in order to reach the goal position.

Based on the above considerations, it appears natural to distinguish between *weak cooperation* and *strict cooperation*. Weak cooperation can be related to what is also required for coordinated motion of AUV teams used for non-manipulative applications, as in [9]–[12], and it is thus present at the beginning of the mission, during the navigation and the grasping phases. On the other hand, strict cooperation is necessary in the transportation phase, where the developed cooperation algorithm presented in [13], [14] is more demanding in terms of data update rate.



(a) Final part of the mission. The vehicles cooperate in order to transfer the object from its original location to a predefined area.



(b) Experimental test of a single-agent grasp operation.

Fig. 1. Conceptual scheme (1a) and experimental testing (1b) within the MARIS project.

A. Communication requirements

Given that the requirements to achieve the loose cooperative tasks are widely treated in literature, we will focus on the communication issues related to joint transportation algorithm, in which the distance between the agents is limited to few meters (typically less than 10 m).

The cooperative grasping and transportation algorithm, developed in the general framework of task priority control, is reported in detail in [13], [14], and is not repeated here for the sake of conciseness. As stated there, the cooperation algorithm requires the exchange of both the linear and the angular velocities of each end-effector, which are used to compute a common reference velocity for the object frame. The packet transmitted through the communication channel is thus constituted by six real numbers encoded as floats, with a total dimension of 24 B per packet. In [15], extensive simulation results of the cooperative algorithm using several configurations are reported. Tab. I summarizes some representative results obtained by running the simulations with the same initial conditions and final reference position and different communication rates. In particular, each of the considered communication rates, 1 Hz half-duplex, 1 Hz full-duplex and 100 Hz full-duplex,

Tab. I
SIMULATION RESULTS OF THE COOPERATIVE TRANSPORTATION ALGORITHM WITH DIFFERENT CONFIGURATIONS.

Test no.	Comm.	Comm. rate (Hz)	Force mod.	Delay (s)	Force (N)			Moment (Nm)		
					Max	Mean	Std. dev.	Max	Mean	Std. dev.
2	NO	–	NO	–	63.29	41.53	18.09	25.78	13.52	5,9
6	HD	1	NO	1	78.5	29.03	17.29	14.55	5.11	3.34
8	FD	1	NO	1	10.1	5.42	2.53	6.71	1.87	0.81
5	FD	100	NO	–	9.9	1.78	1.72	5.13	0.99	0.75
20	NO	–	YES	–	9.64	2.66	2.25	16,02	5.99	2.52
7	HD	1	YES	1	33.6	4.4	5.63	7.75	2.33	1.44
14	FD	1	YES	1	5.07	1.14	1.12	5.63	1.19	0.8
24	FD	100	YES	–	5.03	0.89	0.9	5.7	0.82	0.92

correspond to a specific hardware installed on-board each vehicle: an acoustic modem, two acoustic modems working at different frequencies and an optical system, respectively. A brief explanation of the columns is reported here:

- *Comm.*: it reports the kind of communication scheme employed by the two vehicles. It can be 'NO' (no cooperation between the agents), 'HD' (half-duplex communication) or 'FD' (full-duplex).
- *Comm. rate*: it reports the data exchange rate between the vehicles, if communication is present. It can be set to 100 Hz (the two vehicles communicate at each control loop) or 1 Hz (the two vehicles communicate once every second). In case of half-duplex communication, the AUVs talk to each other in an alternate mode.
- *Force mod.*: it reports if the tool velocity is modified by adding a velocity component along the direction of the interaction force. In the cooperative scheme, this is done after computing and filtering the mean velocity. In the non-cooperative case, this is done during the 'single' vehicle control.
- *Delay*: it reports the total time elapsed between the generation of the packet and the reception at the application level. It includes the processing, transmission and propagation delays.
- The last six columns report the interaction forces and moments between the floating manipulators and the object. The interaction should be minimum to avoid unwanted stresses of the shared object.

Given the closeness of the vehicles, some simplifications can be assumed in the simulation scenario: for instance, the expected packet loss is not high enough to affect significantly the overall performance and thus no loss effects are considered. Also, the delay in case of optical communication system (100 Hz communication rate) can be neglected. Exchanged velocities, when communication is enabled, are always filtered with a cut-off frequency of 10 Hz. Furthermore, 'Force mod.' requires to know the direction of the interaction force, which can be evaluated by measuring the interaction force itself.

For this kind of task it is not straightforward to find a proper index to assess the satisfactory level of the mission performance. However, a measure of the validity of the cooperative algorithm can be given in terms of stability of the overall system and average interaction forces and moments with respect to the non-cooperative case. In all the simulations the vehicles reach the goal position, maintaining the joint grasping of the object. As it can be noticed, cooperation between the vehicles is generally effective in improving the mission performance, even in the case of low communication rate. In particular, when the 'Force mod.' is not enabled (first four rows) data exchange always reduce the average interaction between the agents and the object. On the other hand, when the 'Force mod.' is enabled, (last four rows), the only case in which the cooperative algorithm partially provides worse results with respect to the non-cooperative one is the Test 7, in which the communication is realised in a half-duplex way. However, the interaction force depends on the status of the tasks with higher priority with respect to the vehicles motion (collision avoidance, good manipulability, etc.) and , as previously mentioned, it is not the only meaningful performance index of the algorithm. Moreover, the measurement of the interaction force is not trivial to obtain in practice; hence, the configuration without the 'Force mod.' is more realistic.

III. COMMUNICATION STRATEGY

As for the communication system, each vehicle is equipped with a S2CR 18/34 underwater acoustic USBL system by EvoLogics, a device with modem and positioning capabilities. This system offers two types of media access algorithms, one for big data transfer (*burst data*) and the other for instant bidirectional exchange of short messages up to 64 B long, namely *instant messages* (IMs). IMs are transmitted with a constant bit rate of 976 bps, regardless of the acoustic channel conditions. For the purpose of the cooperative transportation task, given the small dimension of the exchanged data, IMs are the most appropriate option among the two offered by the modem.

The communication delay is composed by two terms: the *transmission time*, i.e. the duration of the physical transmission of a packet, and the *propagation time*, i.e. the delay due to the data flowing through the acoustic channel. The former depends on the packet size only, while the latter is determined by both the sound speed in water and the distance between the acoustic modems. Fig. 2 shows the transmission time as recorded in our experiments with a pair of EvoLogics USBL systems at increasing packet payload sizes. Red crosses are the real data notified by the USBL device, while the solid blue

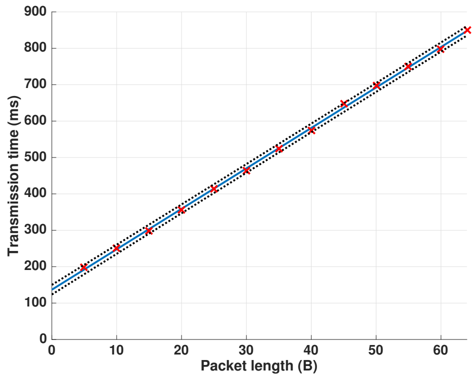


Fig. 2. Transmission time of the EvoLogics USBL system for increasing packet size. It can be seen that the bit-rate is almost constant. Furthermore, in addiction to the effective payload, the system sends few overhead data.

line represent the interpolation of the raw data with a linear function. As can be seen, the transmitted packet is sent with a constant bit-rate and it contains some overhead in addition to the effective packet payload. Regarding the propagation time, it can be trivially computed as the ratio of the distance between the two vehicles and the sound speed.

As previously stated, the cooperative algorithm [13], [14] requires the exchange of a 24 B long packet, so the transmission time for the considered task is about 403 ms. Moreover, considering the sound speed constant to a value of 1500 m/s and the distance between the agents during the joint transportation task limited to few meters, the propagation time results less than 7 ms. Consequently, the total communication delay is about 410 ms, which allows to achieve an half-duplex communication at a maximum rate of 2 Hz. Note that, given the closeness of the vehicles, the error in the evaluation of the propagation time due to the use of an approximated value of the sound speed is of the order of 1 ms and it can be easily neglected.

Although this communication rate may be theoretically sufficient to obtain reasonable results, as shown by the simulations in Tab. I, the operational effectiveness of the cooperative algorithm with such a communication delay will be investigated in practice with the experiments scheduled for the near future. The alternative use of high-bandwidth optical modems [16] is currently under investigation, as an alternative for communication at short range. In particular, the optical modem described in [16] has shown in experimentation robustness with respect to daylight variations, and could provide significant improvements in terms of bit-rate (up to 10 Mbps) at a distance of few meters, as it happens during the transportation phase. However, the use of such modems introduces other issues (for instance, occlusions) at the moment still under investigation because of their impact on the overall system design.

IV. Conclusion

In this paper the communication issues related to the MARIS project have shorty described. The project aims at enabling two autonomous underwater vehicles to jointly grasp, manipulate and transport a shared object. Within such a cooperative scenario, data exchange becomes critical during the transportation phase, where the cooperative control algorithm requires a minimum communication rate of 1 Hz half-duplex. The available acoustic modem allows to achieve a maximum communication rate of 2 Hz half-duplex, which can be theoretically enough for the control purposes, as shown by the simulations. The experimental validation of this scheme will be provided in the near future. However, in case of negative response, high-bandwidth optical modems are currently being investigated as alternatives to acoustic transmission at short range.

Acknowledgment

This paper has been partially supported by Project MARIS, PRIN project no. 2010FBLHRJ_005, funded by MIUR, Italian Ministry of Education and Research.

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