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Cooperative localization of a team of AUVs by a tetrahedral configuration

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HIGHLIGHTS

- An innovative cooperative localization algorithm for AUVs has been designed.
- Acoustic modems for communication are used as sensors of relative distance.
- The method is based on geometric relationships of a tetrahedral configuration.
- The algorithm performance are tested through a complete simulation model.
- A periodic reset of the estimation error is obtained for all the AUVs of the team.

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ABSTRACT

This paper investigates the principles of a Cooperative Localization Algorithm for a team of at least three Autonomous Underwater Vehicles (AUVs) with respect to a surface support ship, without the use of Ultra-Short Baseline (USBL). It is assumed that each AUV is equipped with a low-cost Inertial Measurement Unit (IMU), a compass and a depth sensor, but only one of them has a high accuracy navigation sensor such as the Doppler Velocity Log (DVL). The surface boat locates itself by means of Global Positioning System (GPS). Range measurements provided by acoustic modems allow to avoid an unbounded error growth in the position estimate of each AUV. A geometric method, based on a tetrahedral configuration to obtain a deterministic fix for position, is proposed. This method allows to extend the advantages of the use of the DVL to the position estimate of other vehicles not equipped with DVL. The paper addresses also some of the problems related to the limitations of acoustic communication. The algorithm has been implemented and tested in simulations for a fleet of three AUVs and a surface support ship.

1. Introduction

The underwater localization of AUVs is a challenging issue due to the unavailability of GPS and the techniques developed for surface and/or aerial robotic systems [1,2] cannot directly be extended to the underwater scenario. Navigation systems that fuse information from sensors such as IMU and DVL are characterized by estimate errors between 0.5% and 2.0% of the distance travelled, with the assumption of vehicles not too far from the bottom, so that the DVL has a lock on it [3]. A solution to avoid the error growth could be the deployment of a position update through GPS by frequent surfacing of the AUV [4,5] but this is impossible under ice or undesirable for many applications such as deep sea navigation. An alternative for the position reset is the use of Long Baseline (LBL) systems in which a vehicle triangulates its position from acoustic ranges within a network of transponders [6]. The use of static beacons has the drawback to limit the operational area and to increase the operational costs of the mission at hand. Modern USBL systems feature a transducer array employed to determine the spherical coordinates of several vehicles [7,8] with respect to the USBL reference frame. In this paper the use of acoustic modems as an alternative to localization by means of USBL or as a backup solution in case of failure of the USBL itself is investigated. Commercially available acoustic modems are used for communication among the vehicles of a team and offer the possibility of computing the time of flight from a vehicle to another one. Thus it is possible to calculate the distance between the two vehicles [9]. The problem of observability of the relative motion of two AUVs equipped with acoustic modems, configured as range measuring

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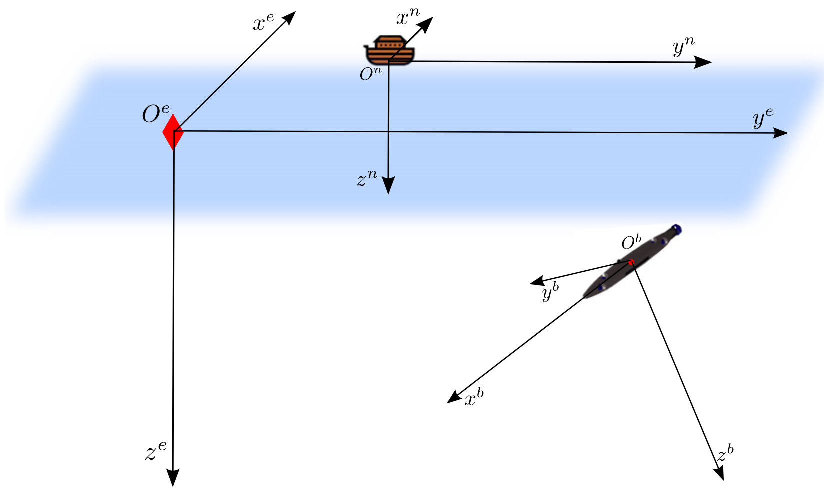

Fig. 1. Definition of body, support and earth frames.

devices, is dealt with in [10]. Several researchers have investigated the cooperative navigation between a surface ship and a single AUV, through Synchronous-Clock One-Way-Travel-Time Acoustic Navigation [11,12]. Recently, many interesting and important works concerning underwater cooperative localization and range measurement based localization have been carried out and many bibliographic references can be found in the literature [13,14]. As concerns, instead, range measurement based localization, interesting approaches are discussed in [15–17]. Bahr et al. [3] proposed a configuration where a dedicated Communication and Navigation Aid-AUV (CNA) can maintain an accurate estimate of its position through high accuracy sensors, such as DVL, and can enable a much larger group of vehicles with less sophisticated navigation suites to maintain an accurate position, too.

The proposed technique is based on a set of distance measurements among four vehicles that travel on the same working area. A geometrical algorithm, fed with the distance measurements, is then able to calculate the relative positions of all the vehicles with respect to the one that works on the surface and that has access to the GPS signal. Thus, different from the approaches in the literature that use range measurements as inputs of the navigation filter, the proposed method uses the range measurements to perform a geometrical algorithm, the outputs of which (the position estimates) are used in the correction step of the navigation Kalman filter.

The approach proposed in this paper relies on AUVs with low-cost instrumentation: each of them is equipped with a low-cost IMU, a compass and depth sensor, but only one of them, the master, has a high accuracy navigation sensor such as the DVL. The system used to highlight the performance of the proposed algorithm is composed of three AUVs and a surface support ship equipped with GPS, but the results could be generalized to a system with a general number of vehicles, at least one of which with the DVL on-board.

The core of the localization algorithm is the *Tetrahedron-based Position Estimator*, a geometric algorithm that is performed on the master AUV. Unfortunately, part of the necessary data is measured on other AUVs and is made available to the master AUV by means of communication. The paper investigates some of the limits imposed by communication, providing a strategy to overcome this problem.

No constraints about the path or hypotheses on mutual distance among AUVs are necessary for the proposed algorithm; particularly the vehicle trajectories may be completely general and no limitations on the related distances are required. The algorithm has been tested in a simulated scenario. The modelled AUV is the "Tifone", a hybrid vehicle under development by MDM Lab, the Laboratory of Mechatronics and Dynamic Modelling of the University of Florence, partner of the Thesaurus project, funded by Regione Toscana, to be used, in a fleet of three vehicles, for research and monitoring of the archaeological sites.

Table 1
Commonly used underwater vehicle navigation sensors.

Sensor	Update rate	Reference frame
IMU	100 Hz	Body
Magnetic compass	100 Hz	Body
Pressure sensor	10 Hz	Earth
DVL	7 Hz	Body
Acoustic modems	Medium: 0.1 Hz	–

Finally, also the robustness of the procedure against numerical noise and model uncertainties have been tested. At the same time, the performances of the new algorithm based on the Tetrahedron-Based Position Estimator have been compared with those of the standard localization procedures to highlight the impact of the innovative algorithm.

Section 2 deals with the most common sensors used in an underwater scenario. The Architecture for Communication and Estimation is outlined in Section 3. In Section 4 the innovative *Tetrahedron-based Position Estimator* is explained. The results of the proposed Localization Algorithm in simulated scenarios are reported in Section 5.

2. Sensors

Underwater navigation algorithms are commonly based on different types of sensors. The sensors considered in numerical simulations are: IMUs, compasses, pressure sensors for depth, DVL (only on the master vehicle), acoustic modems. Sampling periods, reported in Table 1, are derived by the datasheets of commercial sensors.

First, the reference frames characterizing the system are defined (see Fig. 1):

Body frame b

The origin, O_b, is located in the vehicle centre of mass and axes aligned with the axes of the vehicle: x^b axis pointing towards the front of the vehicle, z^b axis pointing down and y^b to complete a right-handed frame.