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Mobile beacon control algorithm that ensures observability in single range navigation ⋆

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Abstract: Mobile beacon vehicles are used as navigational aid for autonomous underwater vehicles when performing navigation using single range measurements. They remove the constraints imposed on the underwater vehicle trajectory by executing trajectory that provides persistent range measurements. In this paper, control algorithm for beacon vehicle which ensures observability of the underwater vehicle's navigation filter is presented. It is characterized by small communication overhead, low computational complexity and it is deployable on both fully actuated and underactuated vehicles. The algorithm was tested in real–life environment and the acquired experimental results show that despite the presence of uncertainties and communication delays, the algorithm accomplishes its task.

Keywords: Navigation, Autonomous vehicles, Kalman filters, Observability indices, Marine systems

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1. INTRODUCTION

Underwater localization and tracking of underwater targets presents a great challenge in marine robotics due to absence of global positioning signals that are usually available in areas reachable by satellites. In order to tackle this problem, acoustic based sensors such as LBL (long–baseline), SBL (short baseline), USBL (ultra–short baseline) are used for underwater localization and navigation, by triangulating responses obtained from acoustic beacons. While LBLs require inconvenient deploying of underwater beacons around the operational area, USBLs that enable relative underwater localization using acoustic propagation are most often used for tracking underwater objects. Both systems are either difficult to deploy or expensive.

In order to overcome these problems in some situations, a navigation method of using range measurements from a single beacon can be applied. The general assumption is that an AUV is trying to navigate underwater (determine its position in the global frame) by using proprioceptive sensors (DVL and/or inertial measurements) and range measurements from the beacon that is stationary or mobile at the surface and knows its absolute position.

Nonlinear systems can be poorly or non-observable along specific state and output trajectories. Ensuring the observability of range-only navigation systems is an important issue and there is a great number of papers dealing with that specific topic (Batista et al. (2011); Crasta et al. (2013); Arrichiello et al. (2015)). In order to estimate its position, the vehicle that is navigating using range measurements from a stationary beacon needs to preform trajectories that provide enough information. In Arrichiello et al. (2013), observability metric for range–only navigation based on the condition number of the observability matrix is used to characterize such trajectories. The action of executing an informative trajectory clearly distracts the AUV from performing its original mission. In Böhm et al. (2008), approaches to avoid weakly observable trajectories in the frame of nonlinear predictive control are presented. By using term in the cost functional that penalizes weakly observable trajectories and thus leads to avoidance of weakly or non-observable regions of operation, trade–off between following predefined trajectory and good degree of observability is achieved. In order to completely avoid that trade–off, it is left to the beacon to ensure informative measurements, thus resulting in the scenario of *mobile beacons*, which is considered in this paper. There is a number

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of ways of determining the optimal trajectory of a mobile beacon. In Moreno-Salinas et al. (2013), the optimal trajectory to ensure observability of static target is found by maximizing Fisher Information Matrix determinant, while in Tan et al. (2014) dynamic programming and Markov decision process approach is used.

The goal of the algorithm presented in this paper is to steer the mobile beacon in order to decrease the localization error of the single range navigation system by using an online algorithm with the very low computational and communication demands. The proposed method is particularly interesting for underwater applications because of the limited bandwidth of acoustic communications. In the control loop, the only data that needs to be transmitted over the acoustic link is the current cost function value which is sent from the vehicle to the beacon, and the current beacon position data. Optionally, beacon velocity can be sent in order to improve localization performance. Furthermore, the proposed algorithm does not require knowledge of the target vehicle's trajectory in advance. That can be particularly useful in real–life conditions when planned trajectories can be altered due to some unexpected situations.

The main motivation for the presented work arises from the FP7 "CADDY - Cognitive Autonomous Diving Buddy" project that has the main objective to develop a multicomponent marine robotic system comprising of an autonomous underwater vehicle (AUV) and an autonomous surface marine platform that will enable cooperation between robots and human divers. In the context of the CADDY project one of the main prerequisites for executing envisioned control algorithms and ensuring diver safety during human-robot interaction is diver position estimation. Single range measurements can be used in order to achieve this requirement. The movement of the diver is usually slow and unpredictable, therefore all the techniques which use a priori knowledge of the target trajectory are not the best choice for determining a beacon's trajectory that makes system observable. The proposed algorithm is especially suited for such application.

This paper is organized as follows. Section 2 describes the concept of using a mobile beacon, guided by the proposed control scheme, to increase the underwater vehicle's quality of navigation by increasing degree of observability. Also the observability cost function is presented. In Section 3 control scheme is described. Experimental results acquired during field trials are given in Section 4.

2. CONCEPT DESCRIPTION

The vehicle has to perform a sufficiently informative trajectory in order to estimate its position using single range measurements. This can prevent the vehicle from doing other useful activities which require trajectories that are not informative enough. To avoid that, an approach with two vehicles, where one of them is a beacon, can be used. In that case, a mobile beacon, which knows its position accurately (from GPS), is responsible for assuming a trajectory which will provide informative range measurements for the target vehicle's navigation filter.

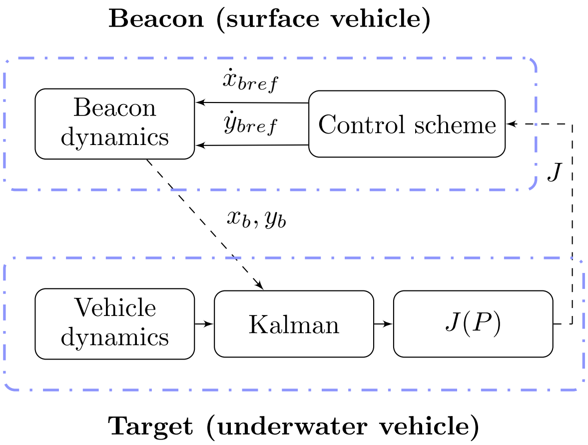

Fig. 1. The concept of observable trajectory tracking using extremum seeking based control scheme. Dashed signals represent acoustic communication.

Figure 1 depicts the main idea which enables better vehicle position estimation by using single beacon measurements. The mobile beacon sends its position (x_b, y_b) to the vehicle's Kalman filter used for navigation. Optionally, the beacon's velocity $(\dot{x}_b, \dot{y}_b)$ can be sent in order to improve localization performance. Information generated in the target vehicle's navigation filter is then used to calculate cost function value J which gives a measure of observability. The current cost value is then sent to mobile beacon which tries to minimize it online by using an extremum seeking scheme which steers the mobile beacon towards the minimimum of the cost function. The beacon again sends its position to the vehicle, thus closing the control loop. The range measurement used for determining the vehicle's position is acquired during the acoustic communication cycle. We consider the state–space representation of vehicle – beacon system relative position in horizontal plane, given with (1).

$$\begin{bmatrix} \Delta\dot{x} \\ \Delta\dot{y} \end{bmatrix} = \begin{bmatrix} \Delta v_x \\ \Delta v_y \end{bmatrix} + \boldsymbol{\zeta} \tag{1}$$

The state vector is given with $\boldsymbol{x} = \left[\, \Delta x \;\; \Delta y \,\right]^{\mathrm{T}}$ where $\Delta x = x - x_b$ and $\Delta y = y - y_b$ are relative positions. The inputs Δv_x and Δv_y are relative speeds between vehicle and beacon in Earth–fixed coordinate frame produced by actuators, sea currents or some other disturbances that act on the vehicle and the beacon, while $\boldsymbol{\zeta} \in \mathrm{R}^{2\times 1}$ represent process noise. Depending on the vehicle's sensor configuration, some of the quantities acting on the vehicle cannot be measured, so they can be considered as process noise. In order to execute the proposed algorithm, the beacon vehicle does not need to know the target vehicle's dynamic and kinematic properties and there are no special requirements on the vehicle or beacon dynamics necessary to execute the algorithm except that the beacon's absolute maximum velocity must be much higher than the target velocity. The system measurement is represented by the Euclidian norm between the vehicle and the beacon position as:

$$r = \sqrt{\Delta x^2 + \Delta y^2} + \nu, \tag{2}$$

where $\nu \sim \mathcal{N}(0, \sigma)$ is measurement noise modelled as Gaussian white noise with variance σ. Equation (2) represents the range in horizontal plane, however, the acoustic