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Homing a robot with range-only measurements under unknown drifts

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HIGHLIGHTS

- Based on range-only measurements, it is possible to home an autonomous vehicle.
- The homing maneuver does not need for solving localization problem.
- By imposing constraints, a control law that guarantee convergence to home is derived.
- An upper bound on the invariant set around the home position is determined.
- Robustness is demonstrated through in-water trials.

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ABSTRACT

The problem of homing a mobile robot to a given reference location under unknown relative and absolute positions is addressed in this paper. This problem is easy to solve when all the positions and kinematic variables are known or are observable, but remains a challenge when only range is measured. Its complexity further increases when variable and unknown drifts are added to the motion, which is typical for marine vehicles. Based on the range measurements, it is possible to drive the robot arbitrarily close to the reference. This paper presents a complete solution and demonstrates the validity of the approach based on the Lyapunov theory. The use of models, which are often affected by uncertainties and/or unmodeled terms, is intended to be minimal and only some constraints are imposed on the speed of the robot. We derive a control law that makes the robot converge asymptotically to the reference and prove its stability theoretically. Nevertheless, as it is well known, practical limitations on the actuation can weaken some properties of convergence, namely when the system dynamics require increasing actuation along the approach trajectory. We will demonstrate that the robot reaches a positively invariant set around the reference whose upper bound is determined. Finally, we conclude our work by presenting simulation and experimental data and by demonstrating the validity and the robustness of the method.

1. Introduction

Homing of AUVs requires a method that robustly drives the robot to an assigned position. This is a simple task when both home and vehicle positions are perfectly known by this latter but becomes a challenging problem when such information is unavailable. The problem is even more complex when only ranges to home are measured and disturbances affect the vehicle trajectory or the home's position. Therefore, a complete method that considers the undesired – and often neglected – external effects is needed to robustly home an AUV subject to these constraints.

In underwater robotics, absolute and relative localization and positioning of autonomous entities are mainly constrained by the intrinsic strong attenuation of electromagnetic waves and by the poor visibility conditions found in the environment. Thus, the research efforts completed by several authors [1–4] over the last two decades have led to a common solution that explores the trilateration concept for bounded error navigation. The method is based on ranges, indirectly obtained from time of flights (TOFs) of acoustic waves between two or more coordinated entities (e.g., AUV and a navigation beacon). Such systems employ a minimal set from one [5] to three acoustic beacons carefully placed in the operation area.

Along with the advances in sensors, other techniques for navigation have been developed for AUVs. The navigation using only Doppler velocity logger (DVL), inertial measurement unit (IMU) and a compass constitutes a suitable solution even though the error grows with time due to the inherent drifts of the first two sensors. The use of effective equipment in large scale, or long time, operations makes it possible to achieve drift errors below 10 m h^{-1} [6].

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Similarly, feature based navigation using acoustic imaging from side scan sonars or multibeam echosounder has attracted the attention of several research groups (see [7] for a SLAM application, for instance) thus leading AUVs toward the concept of standalone platform. The use of acoustic beacons is compatible with those techniques but may be unavailable for some scenarios such as large scale operation, large deep [8] or under-ice [9] navigation.

Common to those operations is the recovery of the AUV. At the end of a mission, the vehicle may not have a sufficiently accurate position estimate and the recovery point may be placed anywhere (ranges, however, must be measurable). One may imagine several scenarios where there is a low confidence on the position estimate and safe recovery close to a beacon is required. Still, if ranges to the reference are measurable then the homing procedure is realizable by adopting a suitable method. This problem is addressed here by considering that a robot is only able to measure ranges to the beacon.

The main goal of this work is to present a complementary method to home an underwater vehicle without resorting to localization algorithms. The main advantage behind this approach is the possibility of defining a totally predictable and deterministic behavior during the trajectory of the vehicle, while avoiding to rely on estimators which may diverge under unpredicted situations. Indeed, solving the localization problem would make it possible to decouple the navigation process into control and position estimation but would be more demanding and uncertain. This latter approach has been implemented by several authors. In [10–12], the authors proposed a method that exploits an extended Kalman filter (EKF) for vehicle localization, where kinematics variables are taken into consideration along with the water current velocity components and a possible speed bias. The use of EKF requires an initialization procedure to avoid divergence of the estimate. In order to solve this problem, the authors have adopted a nonlinear least squares methods that is composed of a two step procedure which first does not consider currents and secondly improves the complete state estimate with the remaining variables, while relying in a kinematics/dynamics model. A similar approach was presented in [13]. The localization problem is also approached in [14] for relative navigation. A sequence of noncolinear positions and respective ranges relative to a beacon are assumed to be known in order to estimate the position by using nonlinear least-squares recursively. A different approach which employs a particle filter (PF) for initialization and an EKF for navigation was proposed in [5], exploiting the advantages of both estimators. While homing, the vehicle is autonomously able to modify its trajectory in order to improve its position estimate. A priori information on the area is used in [15] to generate an artificial potential field combined with a sliding mode control law to home an AUV to its docking station. The homing task can ultimately be considered as a pursuit game (see [16], for example).

Vision-based homing has been widely implemented in ground or aerial robotics (e.g. [17]) and its concepts have been translated to underwater robotics in some works such as [18]. Although this approach is interesting for accurate positioning and docking in particular, it constraints the vehicle to be relatively close to the target (usually below 10 m) to be able to home. An alternative homing method was proposed in [19] using electromagnetic waves emitted and received by means of large coils placed in both the docking station and the AUV. The overall system makes it possible to compute bearing to the dock at distances up to 35 m in sea water. Bearing was also employed in [20] using an ultra short baseline (USBL) carried on the vehicle. The control law ensures that the bearing angle is null along the trajectory to home. However, it is well known that, in USBL systems, the angle resolution decreases with the distance. Recently, a method has been presented in [21] that only takes into account raw data obtained from an USBL system for deriving a control law to home the vehicle. In [22], an extremum search algorithm is introduced to find the maximum approach rate to the beacon. Nevertheless, the method requires initialization otherwise the AUV may be driven to a stable equilibrium point in the opposite direction of the beacon.

In the present paper, a complete method to guide an AUV to a beacon based on ranges only is proposed. The approach is intended to be minimalistic not only in terms of computational complexity but also in terms of sensor/equipment requirements. The approach is constructed so that no state estimation is needed to robustly drive the AUV to a small neighborhood of the home (beacon) position. At the expense of imposing some constraints, the vehicle is endowed with the ability to track a given gradient, while making the behavior completely predictable. It should be noted that precise localization methods cited above can complement the present work, in the vicinity of the home station, for accurate positioning (e.g. docking). By applying Lyapunov nonlinear theory [23], in Section 3, a velocity control law using Lyapunov direct method is derived to conduct the vehicle toward the beacon without requiring initialization. Motivated by real, practical constraints, an upper bound on the distance that the vehicle is guaranteed to reach is derived in Section 4. In Section 5, the results obtained from real experiments performed in the Douro river during the summer of 2011 are presented, demonstrating the robustness of the exposed method. Section 6 qualitatively compares the presented approach with an estimation-based method used to guide an AUV to a beacon.

2. Problem

Consider the motion of a mobile robot in the tridimensional space. Define $\{I\}$ as the inertial referential frame and $\{B\}$ as the body fixed referential frame with origin coincident with the center of gravity and the x and y-axes being coincident with the surge and sway axes. The robot's absolute linear position in $\{I\}$ is denoted by the vector $\eta_l = [x, y, z]^T \in \mathbb{R}^3$, while its angular position is denoted by $\eta_a = [\phi, \theta, \psi]^T \in \mathbb{R}^3$. The relative linear and angular velocity vectors of the robot, expressed in the $\{B\}$ frame, are given by $\nu_l = [u, v, w]^T \in \mathbb{R}^3$ and $\nu_a = [p, q, r]^T \in \mathbb{R}^3$, respectively. During the operation, the robot is assumed to be subject to the effects of drifts that are represented by $\nu_d = [v_x, v_y, v_z]^T \in \mathbb{R}^3$, expressed in the $\{I\}$ frame. This vector is defined as a general drift vector that includes the effects of several disturbances such as current, waves and wind. Introducing the orthonormal mapping matrix $J(\eta_a)$ from $\{B\}$ to $\{I\}$ parametrized by η_a, the velocity vectors in both referential frames $\{I\}$ and $\{B\}$ are related through the following expression (see [24]):

$$\dot{\eta}_l = J(\eta_a)\nu_l + \nu_d. \tag{1}$$

For trivial reasons, in robotics, it is a common practice to decouple vertical and horizontal motions to ensure independent manipulation of the respective state variables. For example, while moving, an underwater vehicle often has to keep preset distances from the bottom and/or from the surface, independently of the horizontal motion. Thus, several authors consider simplified dynamics and kinematics models assuming that their influences are small enough. Previous works have already proven the validity and the satisfactory performance of this approach in underwater vehicles [24] and in aerial vehicles. In ground robots, several works do not even consider the vertical motion since it is constrained to lie in a two dimensional subspace.

Assuming that the robot is stable in the vertical plane (z and θ) and roll angle (ϕ) is stable and equals zero, we decouple the kinematics model based on (1) as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ r \end{bmatrix} + \begin{bmatrix} v_x \\ v_y \\ 0 \end{bmatrix}. \tag{2}$$