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Planar trajectory planning and tracking control design for underactuated AUVs

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Abstract

This paper addresses the combined problem of trajectory planning and tracking control for underactuated autonomous underwater vehicles (AUVs) on the horizontal plane. Given a smooth, inertial, 2D reference trajectory, the planning algorithm uses vehicle dynamics to compute the reference orientation and body-fixed velocities. Using these, the error dynamics are obtained. These are stabilized using backstepping techniques, forcing the tracking error to an arbitrarily small neighborhood of zero. Simulation results for a constant velocity trajectory, i.e. a circle, and a time-varying velocity one, i.e. a sinusoidal path, are presented. The parametric robustness is considered and it is shown that tracking remains satisfactory.

Keywords: Underactuated AUV; Trajectory planning; Tracking control

1. Introduction

Over the past two decades, a great amount of research has been conducted regarding the operation of autonomous underwater vehicles (AUVs), see Fig. 1. AUVs are playing a crucial role in exploration and exploitation of resources located at deep oceanic environments. They are employed in risky missions such as oceanographic observations, bathymetric surveys, ocean floor analysis, military applications, recovery of lost man-made objects, etc. (Yuh, 2000). Besides their numerous practical applications, AUVs present a challenging control problem since most of them are underactuated, i.e., they have fewer actuated inputs than degrees of freedom (DOF), imposing nonintegrable acceleration constraints. In addition, AUVs' kinematic and dynamic models are highly nonlinear and coupled (Fossen, 1994), making control design a hard task. Underactuation rules out the use of trivial control schemes, e.g., full state-feedback linearization (Khalil, 1996), and the complex hydrodynamics excludes designs based on the kinematic model only. Note that when moving on a horizontal plane, AUVs present similar dynamic behavior to underactuated surface vessels (Aguiar and Pascoal, 2002; Fossen, 1994).

The planar stabilization problem for surface vessels and AUVs, i.e., regulation to a point with a desired orientation, has been studied by various researchers; see for example (Aguiar and Pascoal, 2002; Wichlund et al., 1995; Reyhanoglou, 1997; Pettersen and Egeland, 1999; Pettersen and Fossen, 2000; Mazenc et al., 2002). In these works, it is shown that such vehicles cannot be asymptotically stabilized by continuous time-invariant feedback control laws.

Trajectory tracking requires the design of control laws that guide the vehicle to track an inertial reference trajectory, i.e., a geometric path on which a time law is specified. Existing tracking controller designs for underactuated marine vehicles in use—AUVs and surface vessels—follow classical approaches such as local linearization and decoupling of the multivariable model to steer as many DOF as the available control inputs. According to this methodology, the six DOF vehicle is decoupled into two reduced dynamical systems: a depth—pitch model that considers motion in the vertical plane and a plane—yaw model that studies the motion in the horizontal plane.

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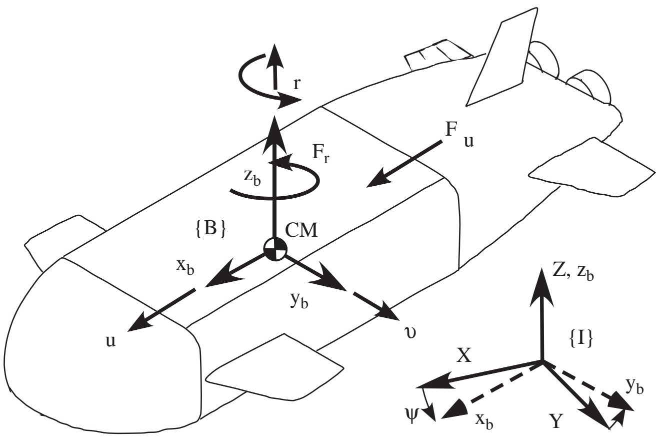

Fig. 1. The underactuated AUV model in plane motion.

The two resulting models are then linearized around a constant nominal forward velocity. Control design is carried out using standard linear (or nonlinear) methods, see (Fossen, 1994). Other approaches include the linearization of the vehicle's error dynamics about "trimming" trajectories—tracking with constant required velocities—that lead to time-invariant linear systems followed by such techniques as gain scheduling, see (Kaminer et al., 1998). The validity of these solutions is limited in a small neighborhood around the selected operating points. Stability and performance also suffer significantly when the vehicle executes maneuvers that excite the effects of its complex hydrodynamics and nonlinear coupling terms.

On the other hand, theoretical and experimental results on trajectory tracking for autonomous underactuated marine vehicles show that nonlinear Lyapunov-based techniques can overcome most of the limitations mentioned above. The authors in Pettersen and Nijmeijer (2001) and Lefeber et al. (2003), present experimental tracking results for a model surface ship using Lyapunov-based controllers. In Jiang (2002), two tracking solutions for a surface vessel were proposed, based on Lyapunov's direct method and passivity approach. However, in the last three works, the yaw velocity is required to be nonzero; under this restriction straight lines cannot be tracked. Also, the drag force model, i.e., the rigid body resistance as it moves through the water is assumed to be a linear function with respect to the velocity in all three DOF motion. This means that the results are valid only when the vehicle moves with low velocities. In Behal et al. (2002), the error dynamics is transformed into a skew-symmetric form and practical convergence is achieved; the authors also consider a linear drag force model. The authors in Aguiar and Hespanha (2003), have designed a controller for marine vehicles moving in two or three dimensions that exponentially forces the position tracking error to a small neighborhood of the origin. However, the attitude is left uncontrolled which may result in position tracking with undesirable attitude. The stabilization of the velocities error is not mentioned as well; this is an equally important matter since even in the case of exact position tracking, large velocity errors may lead to actuator saturation. In Repoulias and Papadopoulos (2005), a trajectory planning and a tracking-control algorithm for an underactuated AUV moving on the horizontal plane were studied. The model of drag force used was linear with respect to velocities; also the planning algorithm was applied for a plane circular trajectory that required constant tracking velocities from the AUV.

In this paper, the combined problem of trajectory planning and tracking control for underactuated AUVs moving on the horizontal plane—constant depth motion—is addressed. The goal of trajectory planning is to generate feasible reference inputs to the motion control system which in turn ensures that the vehicle executes the planned trajectory. Given a smooth 2D reference inertial trajectory, the planning algorithm produces the corresponding reference body-fixed linear and angular velocities and accelerations, as well as the reference orientation. The algorithm is based on the dynamics of the AUV rendering the body-fixed reference trajectory feasible. The trajectories used for the illustration of the method are a circle with constant body-fixed velocities and a sinusoidal curve, which requires time-varying body velocities, i.e., nonzero accelerations. In addition, the drag forces in all three DOF of motion are quadratic with respect to the velocities. Using the resulting reference variables, the vehicle error dynamics is obtained and the control problem reduces to an error dynamics stabilization problem. To this end, methods such as partial state-feedback linearization, backstepping, and nonlinear damping are used to design a time-varying closed-loop trajectory-tracking control law which forces the tracking errors to a neighborhood of zero that can be reduced arbitrarily. A natural requirement in the above procedure is that the surge velocity is nonzero. The robustness in the presence of parameter uncertainty is also studied and the results show that tracking remains very satisfactory. Simulation results that demonstrate the performance of the developed control design are presented and discussed.

2. AUV kinematics and dynamics

In this section, the kinematic and dynamic equations of the motion of an AUV moving on the horizontal (yaw) plane are described. To study the planar motion, we define an inertial reference frame $\{I\}$ and a body-fixed frame $\{B\}$, Fig. 1. The origin of the $\{B\}$ frame coincides with the AUV center of mass (CM) while its axes are along the principal axes of inertia of the vehicle assuming three planes of symmetry: x_b is the longitudinal axis, y_b is the transverse axis, and z_b is the normal axis. Hence, the kinematic equations of motion for an AUV on the horizontal X–Y plane can be written as

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ \upsilon \\ r \end{bmatrix}, \tag{1}$$