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Region tracking based control of an autonomous underwater vehicle with input delay

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ABSTRACT

In this paper, a tracking controller is proposed to navigate the autonomous underwater vehicle (AUV) within a specific region with known constant input delay. The unit quaternion representation is used for attitude control to avoid singularity problem encountered with Euler Angles. However, compensation of actuator delay is a challenging problem to handle with the nonlinear dynamics of an AUV. A predictor based term is thus considered to cancel the input delay term in the open loop dynamics. Nevertheless for some application of an AUV like pipeline inspection or survey it is more practical to define a region as desired position than a specific point. Thus the proposed region tracking controller guarantees an AUV to move within a region for the mission duration. A Lyapunov based stability analysis using Lyapunov–Krasovskii functional is provided to prove uniformly ultimately bounded stability of the closed loop system. Numerical simulations considering a six DOF model of an AUV validate the proposed controller.

1. Introduction

Autonomous underwater vehicles (AUVs) are now on focus of many marine researchers across the globe due to its safe and effective contribution towards various ocean research programmes. Different underwater surveillance missions including military operation and pipeline inspection require an AUV to follow a particular trajectory. In the past few decades many research efforts have been devoted to conventional set point regulation and trajectory tracking problem of an AUV as in Fossen (1994). However, it is interesting to note that most of the AUV missions involve regions as desired target rather than a point or a particular path. A number of underwater missions require AUV to move within a range of depth, maintain the boundary of a pipeline or hover within a region for specimen study.

In lieu of these applications, a new region reaching concept has been introduced by Cheah and Wang (2005) and Cheah et al. (2007) for a robot manipulator while Cheah and Sun (2004) adopted similar concepts for an underwater vehicle. The desired region is specified by an objective function $f(\delta X) \leq 0$ with δX as error in position leading to region reaching control problem. Fig. 1 shows the concept of region reaching where an AUV is moving towards a target of spherical region. Ismail and Dunnigan (2010, 2011) have modified the objective function to address the region boundary based control of an AUV where the region boundary is acting as a constraint. The objective function can be varied accordingly as single objective or intersection of several objective functions as per mission requirement. The objective function can also be modified to act as a repulsive region as proposed by Mukherjee et al. (2014) to solve the problem of obstacle avoidance. However, in some applications AUV is required to move within a constrained region as shown in Fig. 2. Li et al. (2010) proposed an adaptive controller where the desired region is time varying and region tracking control problem has been solved instead of region reaching control problem. In order to achieve fault tolerant control scheme for an AUV while region tracking, Ismail et al. (2013) have proposed an adaptive region tracking based controller where thrusters are fired only if the vehicle is outside the desired region.

Region tracking control concept results in energy saving but does not provide a solution to the problem of large control input. For general feedback control systems with delay in control input, uncompensated errors can grow in the delay interval leading to large actuator command. The literature discussed so far on region reaching based control concept however have not considered any delay in control input. Nevertheless, an extensive amount of research work exists regarding the development of controllers focusing on compensation of input delay. Control problem with input delay was first addressed by Smith (1959) and later on extended by many researchers. Mazenc et al. (2003, 2003) and Francisco et al. (2007) provided fundamental contribution towards input delay problem for stabilization of feed-forward systems. However, to implement these controllers in Euler–Lagrange dynamical system a transformation is required which needs exact model knowledge. Kumar and Dasgupta (2007) have addressed this issue by synthesizing a robust controller for

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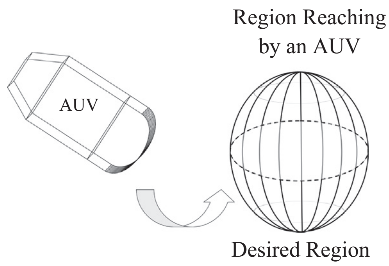

Fig. 1. Region reaching of an AUV.

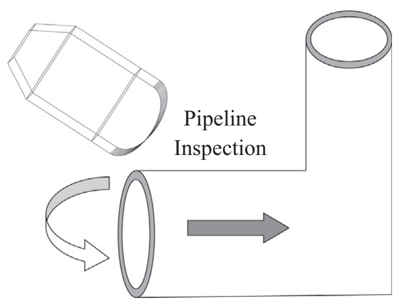

Fig. 2. Region tracking.

underwater vehicles which requires only knowledge of mass matrix. To overcome the problem of input delay in Euler–Lagrange dynamical systems directly, Fisher et al. (2011, 2013), Sharma et al. (2010) proposed a predictor based controller with uncertain system dynamics.

In this paper, a new region tracking controller for underwater vehicle with compensation for input delay is proposed. The required region is defined based upon its potential energy and a relevant term has been used as a contributing factor in the proposed control law. Only one region with specific radius has been considered as desired region which acts as an attractive region. The proposed control law further incorporates an auxiliary signal with integral of past control values. The advantages of the proposed controller are (I) ensures the region tracking of an AUV and (II) compensation of a constant input delay using an auxiliary signal. Further, the unit quaternion representation has been used to avoid singularity in attitude representation. Stability analysis for region tracking based controller with actuator delay has been carried out in the Lyapunov sense. Addition of Lyapunov–Krasovskii (L–K) functional in Lyapunov function is motivated in order to design a delay free open loop system. Choice of appropriate Lyapunov function guarantees uniformly bounded stability of the closed loop system.

The rest of the paper is outlined as follows: Section 2 reviews kinematic and dynamic model of AUV using unit quaternions. The details of region tracking based control and error dynamics leading to controller development are presented in Section 3. Stability analysis of the proposed controller using Lyapunov like function is given in Section 4. Finally, the proposed region tracking control law is simulated on an autonomous underwater vehicle and simulation results in Section 5 validate the effectiveness of the proposed controller. Section 6 concludes the paper with final remarks.

Following notations are used throughout this paper. A^T denotes transpose of matrix A, $\text{Lncosh}(\xi) = [\text{lncosh}(\xi_1), \ldots \text{lncosh}(\xi_n)]^T$ where $\xi = [\xi_1 \ldots \xi_n]^T$. The norm of vector x is defined as $|x| = \sqrt{x^T x}$ and $\|A\| = \sqrt{\lambda_{max}(A^T A)}$ is the norm of matrix A.

2. Model description

The three dimensional equations of motion for AUV have been described by Fossen (1994) using inertial reference frame $\{I\}$ and body fixed frame $\{B\}$ as shown schematically in Fig. 3. As rotation of earth is having little effect on low speed underwater vehicles, earth fixed frame can be considered as inertial frame. The body fixed frame has velocity components in six directions with three linear velocities *surge*, *sway*, *heave* and three rotational velocities *roll*, *pitch*, *yaw* given by the vector ν as

$$\nu = [\nu_1^T \ \nu_2^T]^T = [u \ v \ w \ p \ q \ r]^T \tag{1}$$

2.1. Kinematics

The position of the vehicle can be expressed as $\eta_1 = [x \ y \ z]^T$. However for three dimensional underwater operational space Euler angle representation leads to singularity. So to avoid this singularity problem in attitude representation, Lizarralde et al. (1995) and Lizarralde and Wen (1996) used a four parameter or the unit quaternion representation. Computational efficiency is often considered as added advantage of unit quaternion representation and can be represented as

$$\varepsilon = [\varepsilon_0 \ \ \varepsilon_1 \ \ \varepsilon_2 \ \ \varepsilon_3]^T \tag{2}$$

with Euler axis parameters as scalar ε_0 and vector $\overline{\varepsilon} = [\varepsilon_1 \ \varepsilon_2 \ \varepsilon_3]^T$.

So the vehicle's pose expressed in body fixed frame is related to position and orientation of the vehicle by a velocity transformation matrix given by

$$\dot{\eta} = \begin{bmatrix} \dot{\eta}_1 \\ \dot{\varepsilon} \end{bmatrix} = \begin{bmatrix} R(\varepsilon) & 0_{3\times3} \\ 0_{4\times3} & \frac{1}{2}E(\varepsilon) \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix} \tag{3}$$

where $\nu = [\nu_1; \nu_2]^T$. Rotation matrix is given as

$$R(\varepsilon) = R = (\varepsilon_0^2 - \overline{\varepsilon}^T \overline{\varepsilon}) I_3 + 2\overline{\varepsilon}\,\overline{\varepsilon}^T - 2\varepsilon_0 S(\overline{\varepsilon}) \tag{4}$$

and the quaternion transformation matrix (E) is denoted as

$$E = \begin{bmatrix} -\overline{\varepsilon}^T \\ (\varepsilon_0 I_3 + S(\overline{\varepsilon})) \end{bmatrix} \tag{5}$$

with

$$S(\overline{\varepsilon}) = \begin{bmatrix} 0 & -\varepsilon_3 & \varepsilon_2 \\ \varepsilon_3 & 0 & -\varepsilon_1 \\ -\varepsilon_2 & \varepsilon_1 & 0 \end{bmatrix}$$

2.2. Dynamics

The detail structure of the dynamic equations of motion for an underwater vehicle can be found in Fossen and Sagatun (1991) and Fossen (1994). Due to the hydrodynamic effects acting on underwater vehicle such as added mass coefficients, lift and drag forces, restoring forces, the dynamics become highly nonlinear and coupled. For the velocity state vector $\nu \in \mathbb{R}^6$, the 6 DOF dynamic equation for an AUV can be expressed as

$$M\dot{\nu} + C(\nu)\nu + D(\nu)\nu + g(\eta) = \tau_c(t) \tag{6}$$

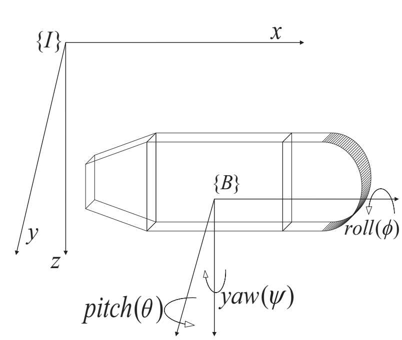

Fig. 3. Inertial $\{I\}$ and body coordinate frame $\{B\}$.