

# Switching Control for 3-D Waypoint Tracking of a Biomimetic Underwater Vehicle

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**This paper addresses the problem of three-dimensional (3-D) waypoint tracking for a biomimetic underwater vehicle (BUV) propelled by undulatory fins: RobCutt-II. Based on the specific mechanical design and control system configuration, the RobCutt-II can perform diversified locomotion patterns, especially submerging or surfacing vertically in the water. For practical underwater operating procedures, a selective switching control for 3-D waypoint tracking is proposed. This control scheme contains a depth controller, a waypoint tracking controller, and a selector. When tracking a series of given 3-D waypoints, the RobCutt-II can switch between two closed-loop locomotion patterns, i.e., the depth control pattern and the waypoint tracking pattern. Simulations and a comparative experimental study demonstrate the feasibility and effectiveness of the proposed switching control scheme.**

## INTRODUCTION

Natural selection and evolution make biological systems diversify into nearly every possible habitat and preserve remarkable adaptations for locomotion (Sang et al., 2005). Mimicking the unique undulatory propulsion mode of cuttlefish, biomimetic underwater vehicles (BUVs) propelled by undulatory fins have many advantages, such as higher maneuverability, stronger disturbance rejection, and quieter actuation than conventional underwater vehicles equipped with jets or axial propellers (Neveln et al., 2013). Hence, these BUVs are expected to be widely used in marine and military fields (Wang et al., 2017).

As growing research on the wave-like propulsion mechanism and hydrodynamics analysis demonstrates a variety of prospective utilities in undersea vehicles, researchers and engineers have developed many kinds of biomimetic robotic prototypes with fin propulsion. Curet et al. (2011) designed a robotic knife fish with an undulatory propulsor using 32 servomotors to drive the elongated ribbon fins. Hu et al. (2014) developed a robotic undulating model and proposed a control scheme that enabled it to mimic fin ray undulation kinematics of live fish. Rahman et al. (2013) designed a squid-like underwater robot with two undulating side fins simulating stingrays or cuttlefishes. However, although many types of BUVs have been developed, few BUVs have been put into practical applications, as far as we know. There are several possible reasons for this fact. In addition to the complex hydrodynamics and the model uncertainty in an underwater environment, researchers seldom consider closed-loop motion control such as waypoint tracking for these BUVs, which is of primary importance for most applications.

Over the past few years, the waypoint tracking for autonomous underwater vehicles (AUVs) or surface vessels has been an active research topic. Aguiar and Pascoal (2007) proposed a nonlinear

adaptive controller to steer an AUV along a sequence of waypoints. Fredriksen and Pettersen (2006) designed a line-of-sight (LOS)-motivated control law that globally  $\kappa$ -exponentially stabilized an underactuated ship in three degrees of freedom (DOF) using cascaded control theory. Oh and Sun (2010) introduced a model-predictive control for waypoint tracking of underactuated surface vessels with input constraints.

The basic limitation of these approaches is their dependence on precise mathematical models of the vehicles, which are usually difficult to obtain for BUVs. It is relevant to point out that most of the results only solve the problem in the horizontal plane. Only a few authors have tackled this control problem in 3-D space. Furthermore, the control inputs of a BUV with undulatory propulsion are the waveform parameters of the fin surface wave, which are quite different from those of other autonomous vehicles or surface vessels.

In our previous project, the 2-D path following control of a BUV has been investigated. A backstepping-based path following control is proposed to maneuver the BUV to follow a predefined parameterized curve without time constraints (Wang et al., 2018a). In this paper, we provide a positive effort toward solving the 3-D waypoint tracking problem. On the basis of analyzing the locomotion procedures of actual underwater operations of autonomous vehicles, a selective switching control is designed for the waypoint tracking problem in 3-D space. The RobCutt-II can switch between two locomotion patterns, including the depth control pattern and the waypoint tracking pattern, according to different operating states. To deal with the problem of model uncertainty, we design the motion controllers based on active disturbance rejection control (ADRC) techniques, which are commonly used and effective in control engineering. Moreover, a fuzzy logic model is used to build the nonlinear relationship between the propulsive force/torque and the control parameters of the undulatory fins of the RobCutt-II. Thus, the proposed control strategy can be actually applied in the 3-D waypoint tracking of the RobCutt-II. In the end, we investigate its efficacy through simulations and comparative experiments with a physical prototype.

In the remainder of this paper, the modeling of the RobCutt-II is first described in the Modeling of the RobCutt-II section. A switching control for 3-D waypoint tracking is elaborated in the Switching Control for 3-D Waypoint Tracking section. Simulations and comparative experimental results are further provided in

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Received September 25, 2017; updated and further revised manuscript received by the editors January 5, 2018. The original version (prior to the final updated and revised manuscript) was presented at the Twenty-seventh International Ocean and Polar Engineering Conference (ISOPE-2017), San Francisco, California, June 25–30, 2017.

KEY WORDS: Biomimetic underwater vehicle, undulatory propulsion, depth control, 3-D waypoint tracking, switching control.