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Diver Tracking Using Path Stabilization - the Virtual Diver Experimental Results

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Abstract The paper presents experimental results for a diver tracking and monitoring controller. The controller utilizes an existing non-linear path following design to ensure safe manoeuvring around the diver. Controller kinematics is derived in the paper and path following is extended with path positioning to allow improved diver observation. Hardware in-the-loop experiments, presented in this paper, analyse the controller behaviour on a fully-actuated underwater vehicle developed at the Laboratory for Underwater Systems and Technologies (LABUST). During experiments the human diver is replaced with a simulated entity referred to as the virtual diver. Experiments isolate and analyse three main parts of the controller: the approach, path following and diver tracking.

Keywords: marine systems, mobile robots, target tracking, path control, nonlinear control

1. INTRODUCTION

The underwater environment can be considered hostile for human divers due to lack of breathable air, limited communication, changing currents and low visibility which complicate navigation and diver interaction. In comparison, remotely operated and autonomous underwater vehicles (ROVs and AUVs) can easily be equipped with sensors that provide improved underwater navigation capabilities. However, they lack higher cognitive capabilities, as opposed to human divers, to accomplish advanced tasks. In a sense, divers and underwater vehicles exhibit complementary traits making their synergy an interesting research topic.

ROVs already aid and increase diver safety for a few decades, see Wernli and Chapman (2012). However, autonomous vehicles for human–diver cooperation are considered only during the last decade. Among the first autonomous robots to be applied for underwater human-robot interaction is the AquaRobot (Georgiades et al., 2004) where the on-board camera image is analysed to recognize diver motion and subsequently used for underwater diver tracking, see Sattar and Dudek (2007). The problem of AUV manoeuvring in presence of divers is investigated in (Streenan and Du Toit, 2013). In an environment with potentially multiple divers, the AUV uses reactive and deliberative control strategies to accomplish manoeuvring without collisions. Diver following in a simulated environment, with sonar based diver detection, was researched in (DeMarco et al., 2013a). Same authors have shown, on real-world results, the feasibility of diver detection and tracking using sonar images (DeMarco et al., 2013b). Diver tracking, using acoustic localization, was also investigated for autonomous surface vehicles (ASVs) in (Birk et al., 2011) and (Miskovic et al., 2015).

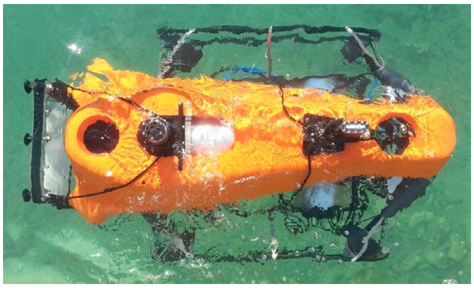

Figure 1. The *Buddy* AUV. Horizontal thrusters are distributed in an X-configuration while the vertical thrusters are located in front and aft.

The European project “CADDY - Cognitive Autonomous Diving Buddy”[1], among other goals, aims to create a diver–robot synergy by creating a cooperative system of an surface and underwater vehicle as diver aids. Part of the system is the AUV shown in Fig. 1, named *Buddy*, which acts as a diving partner and provides constant diver monitoring, guidance, notification, tool fetching and similar services.

Achieving these functionalities requires a set of low and high-level controllers. The tracking and monitoring controller is part of the high-level infrastructure relying on the low-level velocity controllers. In its complete form, this controller enables “guide” and “observer” functionalities envisioned in the CADDY project. While the buddy “guide” has the role to lead the diver towards the point of interest, buddy ”observer” must position itself in front of the diver in order to monitor the diver’s behaviour. The focus in this paper is the buddy “observer” functionality. The controller is based on the virtual target

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[1] CADDY-FP7 web page: `http://caddy-fp7.eu/`

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(VT) approach which is a non-linear path following design where a controller is designed for a "virtual" point onto which the vehicle converges (Samson, 1992) or alternatively converges inside a ball (Aicardi et al., 1995). The approach emphasizes spatial localization, i.e. kinematics, over vehicle dynamics, see Breivik and Fossen (2005b). Previous works deal mostly with under-actuated vehicles that are more common and potentially more challenging. Applications to under-actuated underwater vehicles can be found in (Aicardi et al., 2001), (Lapierre et al., 2003) and (Encarnacao and Pascoal, 2000) for 2D and 3D paths, respectively. In (Lapierre et al., 2003) the limits on the initial AUV position, present in (Samson, 1992) and (Encarnacao and Pascoal, 2000), are lifted by explicit control of the virtual target speed. A general control law for 2D and 3D paths is presented in (Breivik and Fossen, 2005b). This control law was extended in (Breivik and Fossen, 2005a) to the dynamics of a fully-actuated vessel. Similar approaches are also utilized in aerial vehicles (Cunha et al., 2006) where the controller is extended with preview control taking into account the future shape of the path. This article will apply these VT design patterns to a fully-actuated AUV and the problem of path stabilization. Throughout the derivation the notation and terminology from (Fossen, 1994) is followed when applicable.

Initial experiments used for testing the controller introduce the concept of a virtual diver (VD). The VD is a simulated entity participating in a more complex hardware in-the-loop (HIL) simulation. Reasons for replacing a human with a virtual diver is explained in Miskovic et al. (2015) and briefly in Section 3. The article presents a set of experiments performed with the VD and *Buddy* in October 2015, during the Breaking the Surface (BtS) workshop in Biograd na Moru, Croatia.

2. CONTROLLER DERIVATION

The control problem is depicted in Fig. 2. The main reference path corresponds to the desired safety circle and is defined relative to the diver. Note that the path moves with the diver, therefore, ensuring convergence to the path indirectly accomplishes the tracking objective. The fully-actuated nature of the vehicle allows positioning at a desired point on the path, rather than having it continuously move along the path. This allows to accomplish diver monitoring or observation which is required for diver localization, gesture recognition, posture and behaviour estimation tasks. In this paper, the optimal monitoring position is assumed to be directly in front of the diver, as indicated in Fig. 2.

The control subsystem of the underwater vehicle is structured in a cascade fashion and embeds the vehicle dynamics in the velocity control loop. Dynamics is stabilized with a feedback–linearised feed–forward PI controller which tracks feasible set-points and trajectories. Therefore, only the kinematic part of the path following controller is derived in this section.

2.1 Kinematics

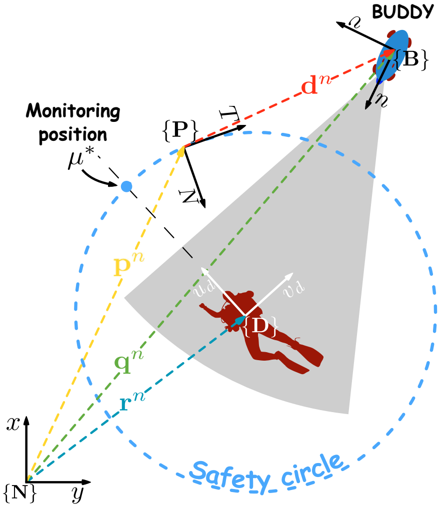

Figure 2. Vector and frame definitions in the diver–*Buddy* formation. During operation Buddy is constantly bound to the safety circle and converges to the desired monitoring position on the path, denoted with μ^*.

Let the navigation (inertial) reference frame be the local tangent plane usually named the North-East-Down (NED) frame and denoted with $\{N\}$. The vehicle position and orientation are commonly defined as $\boldsymbol{\eta}^n = \boldsymbol{\eta} = \left[\boldsymbol{q}^{n^\intercal}\ \ \phi\ \theta\ \psi\right]^\intercal$, where $\boldsymbol{q}^n = [x\ y\ z]^\intercal$. The superscripts denote the frame in which vectors are specified. The position is represented with x, y, z and ϕ, θ, ψ denote the roll, pitch and yaw angles, respectively. Velocities are defined in the vehicle body frame $\{B\}$ as $\dot{\mathbf{q}}^n = \mathbf{R}_b^n \boldsymbol{\nu}_1$, where $\boldsymbol{\nu}_1 = [u\ v\ w]^\intercal$. $\mathbf{R}_b^n = \left(\mathbf{R}_n^b\right)^\intercal$ is the rotation matrix from $\{B\}$ to $\{N\}$. Surge, sway and heave velocities are noted with u, v, w and roll, pitch and yaw rates are denoted with p, q and r, respectively.

The path frame $\{P\}$ is bound to, but can move along, the continuously parametrized path, where $\varpi \in \Re$ is the parametrization variable. The frame, defined by the curve's tangent, normal and binormal unit vectors, is termed the Frenet-Serret frame. The Frenet-Serret frame origin is defined in (Breivik and Fossen, 2005b) as the exact projection point of the vehicle onto the desired path. However, in this article the Frenet-Serret frame is any frame satisfying the above definition, irrespective of its origin. Based on this the speed of frame $\{P\}$ is described with:

$$\dot{\mathbf{p}}^p = \mathbf{R}_n^p \dot{\mathbf{r}}^n + \dot{\varpi}\mathbf{t} \tag{1}$$

with the first term accounting for diver movement and the second for tangential movement along the path. The term $\mathbf{t}$ represents the tangent unity vector $[1, 0, 0^\intercal]$. Finally, the vehicle position in $\{P\}$ is denoted with

$$\boldsymbol{d}^p = \mathbf{d} = [s\ e\ h]^\intercal \tag{2}$$

Only the convergence of $\boldsymbol{d}^p$ is of interest for the path following controller since the AUV orientation is used for other objectives.

It follows from Fig. 2 that $\mathbf{R}_p^n \mathbf{d}^p = \mathbf{q}^n - \mathbf{p}^n$. Proceeding to differentiate the equation gives

$$\mathbf{R}_p^n \dot{\mathbf{d}}^p + \mathbf{R}_p^n \mathbf{S}_p^n \mathbf{d}^p = \mathbf{R}_b^n \boldsymbol{\nu}_1 - \dot{\mathbf{p}}^n \tag{3}$$

where $\dot{\mathbf{R}}_p^n = \mathbf{R}_p^n \mathbf{S}_p^n$ and $\mathbf{S}_p^n$ is the skew-symmetric matrix defined in Breivik and Fossen (2005b). Consider that the