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Cooperative Surface/Underwater Navigation for AUV Path following missions

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Abstract The paper presents acoustic navigation aiding and path following results from demonstration experiments in Lisbon, Portugal. The demonstration was carried out as part of the second year CADDY Review Meeting. The paper presents the concept of the underwater leader, which entails an underwater vehicle, performing a desired task, and a surface vehicle maintaining relative position to improve navigation aiding through acoustics.
The surface controller, utilizing the artificial potential field method, is proposed as an alternative to classical tracking and positioning controllers. Even in presence of multiple agents, the controller offers a more "relaxed" tracking and positioning algorithm for autonomous vehicles. The acoustic data-exchange scheme, required to achieve situation awareness of all agents, is described to specify cycle times and delays that have to be taken into account during state estimation. Finally, results from public demonstrations are presented and analyzed both from the surface and underwater perspectives.

Keywords: marine systems, mobile robots, path following, target tracking

1. INTRODUCTION

The EC-FP7 CADDY project, Cognitive Autonomous Diving Buddy [1] is a R&D research project joining a number of institutions whose areas of expertise complement each other, to develop a system to increase safety, enhance the possibilities and ease a still harsh and dangerous activity as diving. For an overview of the project, see Mišković et al. (2015).

The main idea of the CADDY concept, illustrated in Fig. 1, is to have a system combining robotic vehicles and human divers working in close cooperation resorting to a variety of resources to communicate among them, namely acoustic modems, cameras or sonars, constantly monitoring the humans.

1.1 Vehicles

For the surface vehicle a Medusa-class vehicle was used. Developed at Dynamical Systems and Ocean Robotics Laboratory (DSOR), Instituto Superior Técnico (IST), see Pascoal et al. (2016), there are currently two versions, a surface, as the one used, Fig. 2a and a diver version. Being such a lightweight vehicle and capable of have a wide range of payload sensors, it is a very flexible platform and in this project its objective is to give absolute position to the underwater agents and to relay communications from acoustics to radio and vice-versa.

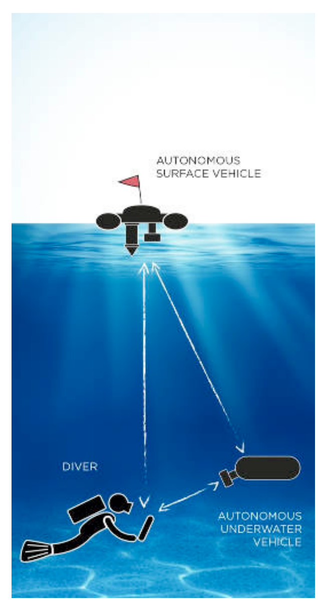

Figure 1. The CADDY concept - a diver with an underwater agents as a slave and diver monitoring platform and a surface vehicle as a communication and absolute navigation relay for underwater agents.

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

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(a) (b)

Figure 2. The autonomous vehicles: (a) the MEDUSA-class as the surface and (b) BUDDY as the underwater agent

The underwater vehicle, named BUDDY, is developed at the Laboratory for Underwater Systems and Technologies (LABUST). BUDDY, shown in Fig. 2b, is fully-actuated in the horizontal plane and can independently control heave and pitch degrees of freedom (DoF). Equipped with a Ultra-Short Baseline(USBL), GPS, DVL, AHRS, mono, stereo and acoustic camera; BUDDY is capable of precise absolute and relative underwater navigation. An underwater tablet, similar to the one carried by the diver in Miskovic et al. (2013), is mounted in front to allow visual interaction with divers. Its main objective in the demonstration experiments is to generate and follow the desired lawn-mower initiated from the diver agent.

1.2 Paper overview

The controller algorithm used on the vehicles are presented in Section 2. Section 3 presents the communication schemes selected for navigation and data-exchange between three agents. The demonstration experiment scenario is briefly presented in Section 4 while results of the trials are shown and in Section 5. The paper is concluded with Section 6.

2. CONTROLLER DESCRIPTION

Two different control strategies were used as the goal of each vehicle role is not the same. The underwater vehicle is required to perform path-following with minimum possible error while the surface vehicle is allowed to be more "relaxed" and maintain position within a region around the agents.

Controllers are implemented inside the Robot Operating System (ROS) framework, Quigley et al. (2009), as ROS nodes. Control inputs are vehicle pose and velocity estimates. The control outputs for path-following are surge and yaw and for surface tracking outputs are surge and yaw-rate set-points.

2.1 Potential field controller

Bearing in mind the requirements that arise from the CADDY concept, there are two main scenarios that the surface vehicle should tackle in order to track the underwater segment:

- BUDDY vehicle following diver: this scenario implies that both underwater agents are performing unstructured/random trajectories;
- BUDDY vehicle surveying an area and diver at rest: in this scenario BUDDY vehicle is performing a structured (lawnmower) trajectory while diver is stopped or has a random walk behavior.

According to these scenarios the underwater agents can perform any type of mission and therefore estimating its position can be an extremely difficult task. For this reason, it is not possible for the surface vehicle to strictly follow the path taken by the other two agents as was done in Abreu and Pascoal (2015), where the trajectories were generated online, but its types where predefined, thus making it possible to generate targets to track.

In CADDY instead, the surface vehicle is only expected to be in a area close-by in order to improve, among other things, the acoustic communications with the underwater agents, while avoiding being on top of them, for safety purposes.

To implement the above strategy in a way that both scenarios are contemplated, an artificial potential field (APF) technique was used. As can be seen in Latombe (1991); Khatib (1985) an *APF* consists basically of the sum of potential fields, one attractive and one or more repulsive:

$$\boldsymbol{U} = \boldsymbol{U}_{att} + \boldsymbol{U}^{B}_{rep} + \boldsymbol{U}^{D}_{rep} \tag{1}$$

where $\boldsymbol{U}_{att}$ is the attractive potential and $\boldsymbol{U}^{B}_{rep}$ and $\boldsymbol{U}^{D}_{rep}$ are the repulsive potential generated by the BUDDY and the diver, respectively.

In this specific case, the idea was to create a potential field that has a basin sloped towards a circle around the midpoint between the BUDDY and the diver and a peak on top of each target with a flat area around it. With this configuration, instead of generating a global minimum point, a global minimum area is created which causes the surface vehicle to have a more relaxed behavior. The function that describes this potential field is given by

$$\boldsymbol{U}_{att} = \begin{cases} 0, & \|\boldsymbol{p}_M\| \le r_i \\ \left(\|\boldsymbol{p}_M\| - r_o + \dfrac{r_o - r_i}{2}\right)\lambda_a, & \|\boldsymbol{p}_M\| \ge r_i \\ \dfrac{\lambda_a}{2}\left[\boldsymbol{d} - sin\left(\dfrac{\boldsymbol{d}\pi}{r_o - r_i}\right)\dfrac{r_o - r_i}{\pi}\right], & \text{otherwise} \end{cases} \tag{2}$$

$$\boldsymbol{U}_{rep} = \begin{cases} 0, & \|\boldsymbol{p}_T\| \ge r_t \\ \left[cos\left(\dfrac{\|\boldsymbol{p}_T\|}{r_t}\dfrac{\pi}{2} + \dfrac{\pi}{2}\right) + 1\right]\dfrac{2\lambda_r r_t}{\pi}, & \text{otherwise} \end{cases} \tag{3}$$

where $\boldsymbol{p}_M$ is the vector between surface vehicle and the midpoint between the two underwater agents, r_i is the radius of the flat area, r_o is the radius where the basin reach its maximum derivative λ_a, $\boldsymbol{d}$ is the distance between the surface vehicle and r_i, $\boldsymbol{p}_T$ is the vector between the surface vehicle and one of the underwater agents, r_t is the distance to the target where the peak starts to grow from zero and λ_r is the maximum derivative of the repulsive potential.