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AUV homing and docking for remote operations

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ABSTRACT

One of the major goals of the SUNRISE FP7 project is to make the Underwater Internet of Things a reality. In this context, the LOON-DOCK project presented here extends the existing Litoral Ocean Observatory Network testbed with a Docking Station tailored to the Sparus II AUV. The docking system allows a remote user to program survey-like missions through a web-based interface as well as to retrieve the data gathered by the AUV once a mission finalizes. To enable the autonomous docking of the AUV, two complementary and cost-effective localization systems have been developed. The first one implements a range-only localization algorithm to approach the docking station while the second, based on active light beacons, provides high accuracy at short ranges to complete the docking maneuver. The system has been extensively tested, in different trials from a controlled water tank environment to more realistic sea operation conditions proving its viability despite very poor water visibility conditions.

1. Introduction

The increased number of deployed subsea systems (infrastructures, sensors, robots, gliders and others) during the last years, is raising the need for interconnection among themselves and to the exterior world, for a better management and exploitation. This is one of the major goals of the SUNRISE FP7 project (Petrioli et al., 2013), which is devoted to make the Underwater Internet of Things (UIoT) a reality. Connecting the underwater systems to the network and endowing them with the capability of making their data widely accessible while minimizing the need of human interaction, has the potential of providing ocean data at an unprecedented scale.

Persistent deployment of buoyancy-driven vehicles (gliders) in open waters has already been achieved for periods of time spanning months (Manley and Willcox, 2010; Meyer, 2016). However, persistent deployment of survey-type Autonomous Underwater Vehicles (AUVs), capable of more complex mapping missions, is a challenging problem that arises the requirement of docking. The objective behind the docking concept is to extend the deployment time by installing a Docking Station (DS) that allows to extract the data of finished missions, program new missions and recharge the batteries of the vehicle without recovering it at the surface. The first systems were designed for oceanographic sampling purposes (Curtin et al., 1993; Singh et al., 2001). More recently, the interest has grown towards using AUVs in commercial scenarios, for the periodic inspection and maintenance of subsea installations (Brignone et al., 2007; Krupinski et al., 2008; Jacobson et al., 2013). In addition, a significant part of docking-related works have emerged from operational environments where launch and recovery is a difficult task such as under ice operations (King et al., 2009). However, despite many demonstrations have taken place since the 90's, the combined need of infrastructure (physical mounting, power, communications) and the demanding vehicle reliability required to operate continuously without human servicing, still makes docking a state-of-the-art problem (Bellingham, 2016).

In the context of the SUNRISE project, the LOON-DOCK project presented here aims to extend the existing Litoral Ocean Observatory Network (LOON) testbed (Alves et al., 2014) with a DS to demonstrate data transmission from a survey-AUV to the Internet. The idea is to be able to remotely operate the AUV from the SUNRISE GATE, (Petrioli et al., 2014), a web interface created to remotely schedule experiments using assets persistently deployed in different testbed facilities around the world. For the AUVs to really become part of the UIoT, it is essential to provide docking solutions that are cost-effective, while maintaining the performance and reliability of the system. In this sense, our proposal strives to keep the implemented docking approach low-cost in all the addressed aspects, namely the mechanical design, the communications and the autonomous docking procedure. The power transference to the AUV is not covered in the scope of this work. However, it is worth noting that solutions for wireless inductive power transference already exist in the market and could be integrated at a certain cost.

From the hardware point of view, the developed DS is based on a

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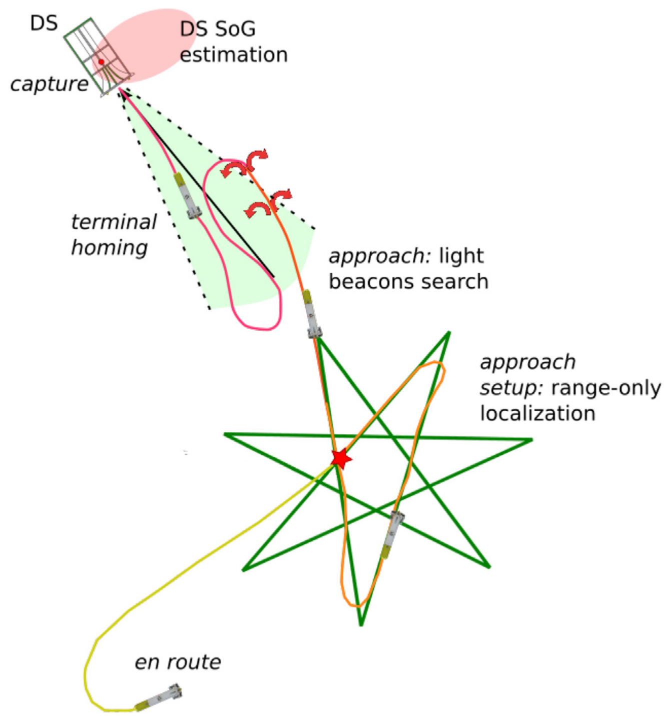

Fig. 1. Docking phases scheme.

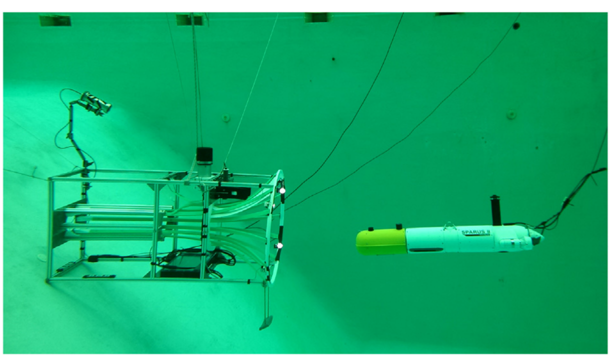

Fig. 2. Testing the docking station and the approach procedures in a water tank. The AUV cable visible in the image is only for monitoring purposes.

funnel-shaped receptacle, which is a traditional solution (Cowen et al., 1997; Allen et al., 2006; McEwen et al., 2008) to physically guide the vehicle into the dock. Another common design found in the literature are the vertical dock poles (Singh et al., 2001; Stone et al., 2010) that allow the vehicle to approach from any direction, making them more robust to changing water disturbances. To alleviate the directionality constrain, the funnel receptacle has been designed so that it can pivot over the static base and be oriented according to the water currents of the environment. Compared to a pole dock, the funnel-shaped design eases the installation of the necessary equipment to support the communications and the homing maneuvers, facilitates the establishment of links with the vehicle and protects the AUV against environmental hazards while docked. With regards to communications, the developed docking system is directly connected to the Internet through the LOON infrastructure, and features two modes of communication with the AUV. The first mode uses an acoustic modem and the SUNSET protocol (Petrioli et al., 2015), a lightweight networking framework well-suited for underwater acoustic communications. The second mode, intended for when the AUV is docked, is based on a contactless WiFi module installed in the DS, which is crucial to transfer at high speed the vast amounts of data that a survey-AUV can gather in a mission. The use of a contactless radio frequency module, based on a commercial off-the-shelf (COTS) WiFi modem, provides a reliable and low-cost data transmission system (McEwen et al., 2008) capable of achieving transfer speeds in the order of tens of Mbps. It does not require the mating of connectors underwater, thus preventing the exposure of electrical contacts, and provides a less sensitive alignment with respect to establishing direct electrical connections (Stokey et al., 2001) or inductive coupling (Feezor et al., 2001).

To assist the autonomous docking procedure, the DS employs the acoustic modem as a range-only transponder for mid-range homing, and a set of light beacons installed in the funnel entrance for the terminal phase of the docking. The autonomous docking is tackled from the general scenario in which the vehicle does not know the exact position of the DS, usually because it has lost the communication with the DS during a mission execution and only has an *a priori* coarse estimate of its position. Then, following the nomenclature established in Bellingham (2016), our proposed approach for autonomous docking works as follows (see Fig. 1): first, the vehicle starts from an *en route* phase, that gets the vehicle close enough so it can sense the DS with the on-board acoustic transponder. This navigation is performed according to the on-board navigation filter that merges information from different sensors to navigate relative to the Earth. Next, in the *approach-setup* phase, a range-only localization filter is used to estimate the DS location while the AUV is guided along an observable trajectory. Once an estimation of the DS position becomes known, the vehicle approaches the DS to bring it within visual reach (i.e., *approach* phase). The light beacon navigation system is used to estimate the DS pose with respect to the AUV on-board camera. Visual information is used to update a single landmark simultaneous localization and mapping filter that provides the relative position between the AUV and the DS with the accuracy required for the *terminal homing* phase. Preliminary versions of these two localization algorithms have been previously reported in a simulation environment (Vallicrosa et al., 2016). In order to back up the visual localization during the very last few meters of the approach, when the light beacons are no longer inside the camera field of view, a complementary system has been integrated using augmented reality (AR) markers (Garrido-Jurado et al., 2014). After this phase, the AUV ends up inside the docking funnel and is guided up to the latch mechanism by controlling the generated forward thrust (i.e., *capture* phase).

Existing solutions to perform autonomous docking usually rely in more complex acoustic sensors including USBL (McEwen et al., 2008; Allen et al., 2006) or inverted SBL setups (Smith and Kronen, 1997). Optical sensors have also been explored for the terminal phase, with solutions comprising either active light sources -with single (Cowen et al., 1997; Murarka et al., 2009; Li et al., 2015, 2016) or multi-light systems (Hong et al., 2003; Park et al., 2009)- or passive patterns and markers (Kushnerik et al., 2009; Maire et al., 2009) that can be detected by on-board cameras. Altogether, our approach provides an hierarchical homing procedure that ensures a reliable approach and terminal homing maneuvers enabled with low-cost equipment and minimal requirements on both the vehicle and the DS sides. Notice that, indeed, the acoustic ranging and optical image acquisition are capabilities that either already exist in most AUVs or can be easily added at a reasonable cost. The same reasoning applies to the docking station, since the light beacon system and the AR markers are relatively inexpensive to manufacture.

The reminder of this paper is organized as follows: next section describes in more detail the employed AUV and the design of the proposed docking station. Section 3 introduces the navigation system of the AUV together with the developed algorithms for autonomous docking, including both the range-only localization and the visual localization of the DS. Section 4 covers the insights about operation and control, involving the remote operation through the SUNRISE web-based