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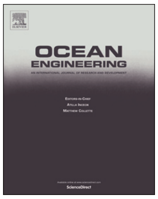

# Autonomous underwater vehicle docking system for cabled ocean observatory network

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ABSTRACT

A new funnel-type autonomous underwater vehicle (AUV) docking system that can be connected to a cabled ocean observatory network is developed to charge AUVs undersea. The main features of the system include non-penetrating power and data transfer without any auxiliary actuators, auto-orientation adjustment of the entrance, magnetic clamping of the AUV, and ultra-short baseline (USBL) and computer vision integrated navigation. A homing control method based on cross-track error for USBL navigation is proposed. Its design goal is to rapidly eliminate cross-track errors and change the behavior of the AUV smoothly without losing USBL signal in lateral current. The prototype system was tested in a water pool. Light tracking, docking, and clamping were successful. The battery of the AUV was effectively charged by the non-penetrating power transfer component at 144 W, during which the non-penetrating data transfer component worked properly.

## 1. Introduction

Autonomous underwater vehicles (AUVs) are useful for exploring deep oceans and have been widely used in recent years (Nicholson and Healey, 2008). However, the limited duration of AUV operation remains a drawback. When the battery of an AUV is depleted, it needs to be recovered and charged. Docking technology is developed to charge AUVs undersea to extend AUV operation and reduce expensive recovery costs. When an AUV is running out of battery, it searches for the docking station (DS) deployed undersea and navigates to it. The AUV is clamped by the DS while the battery is being charged. The fully charged AUV then begins a new mission that has just been uploaded to it. Problems arise from this process. First, AUVs need to detect the position of the DS and then navigates to it in a complex sea environment. Second, a well-constructed DS is required to catch the approaching AUV. Third, the DS needs to lock and unlock the AUV whenever necessary. Fourth, sufficient power is required to be transferred from the DS to the AUV and a communication path between them needs to be established while the AUV is docked.

Most DSs are powered by batteries, which limits the operation time of the DS. The development of cabled ocean observatory networks (COON) (Howe and McGinnis, 2004; Favali et al., 2013) introduces technological opportunities to AUV docking. Connecting a DS to a COON can overcome the limitations of battery life, allowing the AUV and COON to work together to effectively monitor sea environment. The docking technology offers two new means to operate AUVs. First, the DS may work like gas stations distributed in the operation paths of AUVs. Second, they may also work as AUV bases, each of which controls one specific AUV, thereby eliminating the need for AUV recovery. Fig. 1 illustrates the concept of the combination of DS and COON.

As a promising technology, AUV docking systems have been studied by many groups although only a few of them have nearly utilized it for practical use. Singh et al. (2001) proposed a docking system to be installed on the mooring of an autonomous ocean sampling network. It possessed a reliable latch mechanism, a robust homing controller, and a non-contact power and data interface. The system has been verified by relative simulations. Allen et al. (2006) designed a docking station for REMUS100 AUV in which a position detection sensor and a linear actuator were employed for latching and a plugin connector was used for power and data transfer. Out of 29 attempts, 17 docking runs were successful in their experiment. The only reported docking system designed for COON was built by Monterey Bay Aquarium Research Institute (McEwen et al., 2008). It was equipped with USBL navigation system, non-contact power and data transfer system, and actuated latching system. This system has accomplished a 15 m depth sea trial. Besides torpedo-shaped AUVs, docking technologies of intervention AUVs (I-AUV) have also been widely studied (Sotiropoulos et al., 2012; Krupinski et al., 2008, 2009). I-AUVs usually have 6 degrees of freedom and they are aimed to dock on

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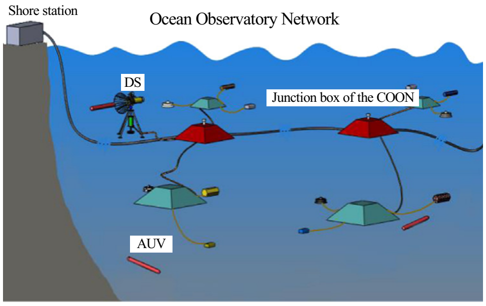

**Fig. 1.** DS connected to COON.

undersea structures for further missions. Sotiropoulos et al. (2012) proposed a homing and docking strategy combined of acoustic localization and visual localization, which can also be adopted in the docking of orpedo-shaped AUVs.

This study proposes a new torpedo-shaped AUV docking system for ocean observatory networks. Section 2 introduces the components of this system. The main features include non-penetrating power and data transfer component without any actuators, orientation adjustable component of the entrance, ultra-short baseline (USBL) and computer vision integrated navigation, and magnetic clamping component. Section 3 proposes a homing control method based on cross-track error for USBL navigation and a light tracking method for optical navigation. The docking system has been tested in a water pool. The AUV successfully entered the DS more than 10 times, with data and power being transferred. Successful light tracking runs have also been conducted. The recorded test results are discussed in Section 4.

## 2. Overall configuration of the DS

Our primary design principle for the docking system is to simplify the operation of the AUV. For example, we prefer multi-directional entry to unidirectional entry because the former forwards fewer requests to the AUV than the latter. Few requests for precise navigation and less AUV refitting are favorable. Several types of DS structures have been proposed, including primarily latch and pole type (Singh et al., 2001), pole and latch type (Coulson et al., 2004; Lambiotte et al., 2002), hook and wire type (Fukasawa et al., 2003), and funnel type (Stokey et al., 1997; Brighenti et al., 1998; Robert et al., 2005; Allen et al., 2006; McEwen et al., 2008; Pyle et al., 2012). In the pole and latch type, a latching mechanism is installed on the nose of the AUV to grab the pole that is fixed on the DS. In the pole and latch type, a pole is installed beneath the AUV to slip into the latch that is fixed on the top of the DS. In the hook and wire type, the AUV drops a hook to catch the wire on the DS, thereby landing on the DS similar to a landing plane. Both methods allow the AUV to enter the DS easily. However, an extra actuator on the AUV is required thereby complicating the refitting of AUV. Funnel type has been more widely used. The entrance of this docking system has a funnel that guides the AUV into the DS passively. Thus, less refitting to the AUV is required and the docked AUV is protected. However, the AUV can only enter the DS in one direction in this type of docking system.

The funnel type is selected in our design after considering various structure types. The overall configuration of the docking system is illustrated in Fig. 2. It mainly consists of two parts: the refitted AUV and the DS.

The front part of the AUV is replaced by a docking shell, which contains a USBL transceiver and a camera for positioning, together with several circuits for data processing and power transfer. An additional structure is attached to the external surface of the shell. It holds a coil for power transfer and an antenna for data exchange. The structure has an 18° slope at the front for a smooth entry. The nose cap of the AUV is made of polycarbonate, a material that is acoustically and optically transparent. The refitted AUV has a length of 2.7 m and a diameter of 200 mm. The external diameter of the attachment is 290 mm.

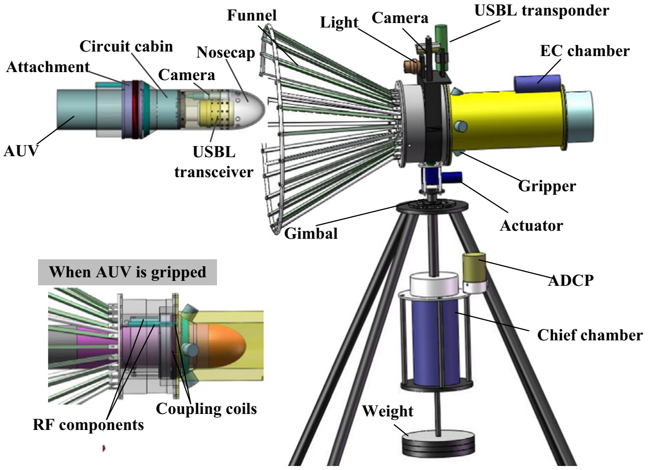

**Fig. 2.** Overall configuration of the proposed docking system.

The DS is designed to stand on the seafloor, connected to a COON. It roughly consists of 11 parts that perform different functions. These parts are the funnel-shaped entrance, an accommodation tube, the base, a waterproof chamber, the USBL transponder, an underwater camera, two underwater lights, a gripper, the orientation component, the balance mechanism, and the data and power transfer components.

The funnel-shaped entrance of the DS has a diameter of 1.1 m and a cone angle of 60°. The successful docking of the AUV is closely related to the shape and material of the funnel and the attitude of the AUV, which has been particularly discussed in our previous work (Shi et al., 2015) and considered as design criteria of the system. The funnel is fixed to the 296 mm diameter accommodation tube mounted on the top of the 2 m-tall base. The control circuits of the DS are insulated in the waterproof chamber settled beneath the base. A wet-mate comes out of the chamber to connect with the COON.

The USBL transponder is fixed atop the DS to provide the AUV with the position of the DS. It has an underwater light and a camera, angled slightly downward. The camera is designed to inspect the docking process in the event of an accident. The light illuminates the AUV to be visible for the camera and provides a landmark for the AUV vision system.

The gripper clamps the AUV after it enters the DS. It is made of three electromagnets, which are turned on by the operator when the AUV is about to enter the DS. When the AUV enters the tube, the magnetic steel on its attachment meets the electromagnets. The AUV is then gripped by magnetic force. Our test shows that 110 N pulling force is required to detach the AUV from the electromagnets. To release the AUV, it is just need to turn off the electromagnets and reverse the propeller of the AUV. This grip method has two advantages. First, it is simple without any actuators or position sensors. Second, it latches reliably and releases easily (by turning off the electromagnets).

The orientation component adjusts the entrance to line up with the ocean current when a docking mission initiates, thereby minimizing lateral current disturbance during the homing process. An ADCP (acoustic Doppler current profiler) fixed on the base of the DS is used to measure the current profiles. Current velocity data are transferred to the motor control circuit and control signals