Remote Real-Time Video-Enabled Docking for Underwater Autonomous Platforms

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ABSTRACT

One of the key challenges in the development and implementation of ocean observatories is sustained observations over relevant temporal and spatial scales. Autonomous underwater vehicles (AUVs) have demonstrated their potential for synoptic spatial coverage of regions of scientific and strategic interest. The range and duration of these systems are limited, however, to the capabilities of a single charge. A few efforts have been made to develop docking systems for propeller-driven vehicles; however, these systems are not applicable for buoyancy-driven gliders and cannot be universally applied to AUVs. Here the authors introduce an alternative strategy for AUV docking, demonstrate feasibility with a series of field tests using a remotely operated vehicle (ROV) to remotely recover an AUV, and comment on the scalability within the framework of the evolving global ocean observatory initiatives. Implementation of simple strategies such as this has the potential to reduce the chronic problem of undersampling in the ocean and may facilitate addressing some outstanding scientific questions related to the ocean.

1. Introduction

The world's oceans are undergoing a number of major changes on generational time scales. Climate change is increasing the upper-ocean heat content in many regions, which, among other things, is changing ice dynamics in the northern latitudes (Hanna et al. 2005; Rapley 2006; Rignot and Kanagaratnam 2006), with significant impacts to polar ecosystems (Moline et al. 2008a). For example, the Wilkes ice shelf in Antarctica began to collapse in February 2008 exhibiting the same behavior as the Larsen ice shelf, which collapsed around 5 yr ago (Shepherd et al. 2003). Projected continued warming associated with the current levels of atmospheric CO_2 will weaken the thermohaline circulation and impact circulation patterns in Atlantic Ocean (Schlesinger et al. 2006). Additionally, the infusion of CO_2 from the atmosphere is decreasing the pH of the ocean, with profound implications for the biology of the ocean (Riebesell et al. 2000; Feely et al. 2004; Iglesias-Rodriguez et al. 2008). The ocean is also losing its apex predators in the collapse of global fisheries with unknown consequences for the regional food webs and biogeochemical cycling (Myers and Worm 2003; Worm et al. 2005). Coastal eutrophication is driving the development of low oxygen ‘‘dead zones,’’ which are increasing in size and occurrence (Rabalais et al. 2002; Dybas 2005; Moline et al. 2008b). These examples of change are occurring globally and will directly impact human society. Understanding how these changes will influence the earth system will require the oceanographic community to significantly improve its ability to synoptically sample the oceans over a range of scales for sustained periods of time.

For centuries, oceanographers have relied on observations gathered from ships during expeditions of limited duration. In addition to the limited duration, it is often difficult for ships to sample the ocean under many conditions, such as storms, known to be critically important to ocean physics, chemistry, and biology (Glenn

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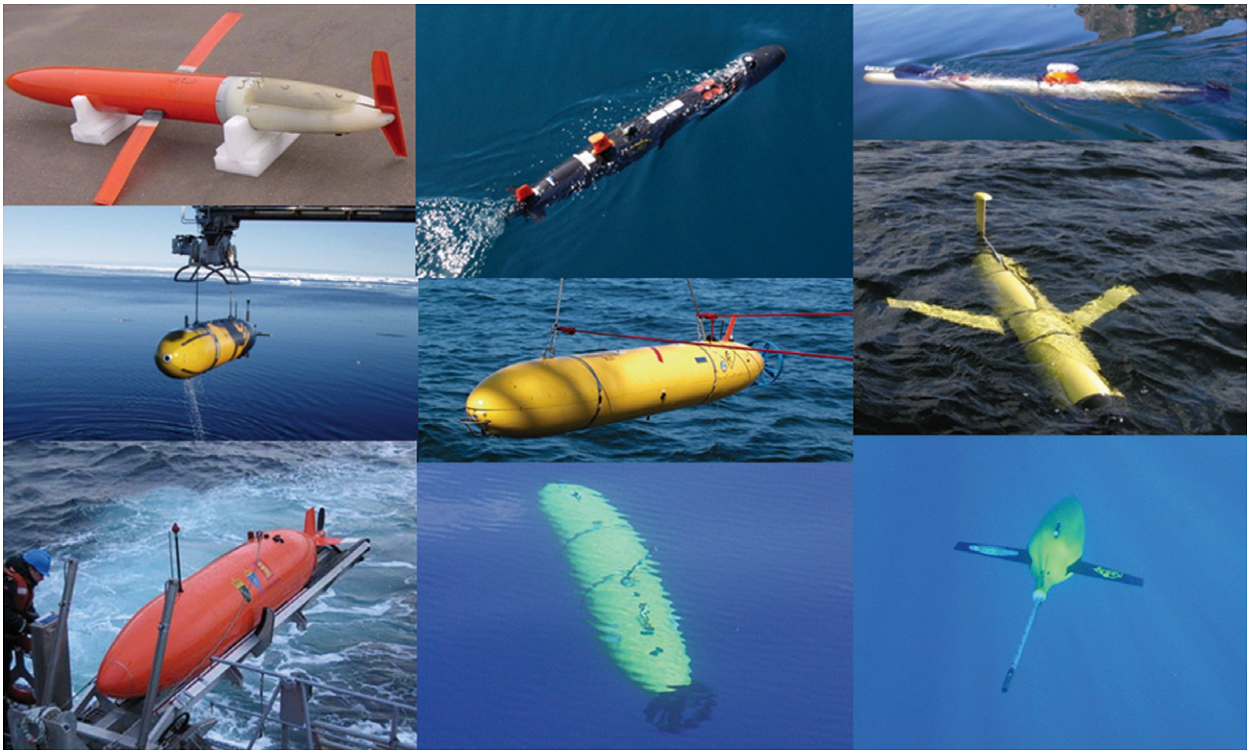

FIG. 1. Examples of currently available AUVs, illustrating the diversity in size and shape in AUV systems. (from the top left) Spray glider (http://www.bluefinrobotics.com/), REMUS-100 (http://www.hydroidinc.com/), Gavia (http://gavia.is/), Autosub II (http://www.noc.soton.ac.uk/aui/), Dorado (http://www.mbari.org/AUV/), Slocum glider (http://webbresearch.com/), Hugin (http://www.km.kongsberg.com/), Bluefin-21 (http://www.bluefinrobotics.com/), and Seaglider (http://irobot.com/).

et al. 2008). The advent of remote sensing was a major revolution for synoptic ocean sampling (Munk 2000; McClain 2009); however, these remote sensing techniques can only sample the upper surface of the ocean. This observational gap has led the scientific community to consistently call for a capability to maintain a continuous presence within the ocean (National Research Council 2003; Schofield and Tivey 2005). The introduction of seafloor cables, high-powered moorings, and autonomous mobile platforms offer the potential for the next revolution of ocean sampling by ushering in the era of real-time subsurface remote sensing. For these subsurface networks to achieve their potential, they will to need operate as an integrated network with systems being capable of adaptively sampling the ocean. Scientific communities around the world (Canada, China, the European Union, Japan, and the United States) are designing and implementing seafloor (Schofield et al. 2002; see online at http://www.venus.uvic.ca/) and moored ocean observatories (Frye et al. 2004) in order to provide the infrastructure backbone providing power and bandwidth that can support water column profilers and mobile assets. For the science, mobile assets are especially critical to the observatory design as they provide the spatial context for the fixed platform time series measurements and data assimilative models (Chao et al. 2008).

Mobile platform technologies have matured and transitioned from specialized engineering/science teams to mainstream applications, supporting the larger scientific community (Rudnick and Perry 2003). Results from early science missions are now becoming available, significantly improving our understanding of spatial phenomena and processes (see the special issue of *Limnology and Oceanography,* 2008, Vol. 56). There are generally two classes of mobile platforms or autonomous underwater vehicles (AUVs): gliders and propeller-driven vehicles (Fig. 1). Autonomous gliders change buoyancy and use wings to convert a fraction of their vertical motion into horizontal velocity. Typical speeds are on the order of 0.25 m s^{-1}. These systems are designed to patrol the subsurface for weeks to months at a time, surfacing to transmit their data to shore while downloading new instructions at regular intervals (Eriksen et al. 2001; Sherman et al. 2001; Webb et al. 2001; Davis et al. 2003; Schofield et al. 2002; Schofield et al. 2003; Castelao et al. 2008; Davis et al. 2008; Perry et al. 2008). The propeller-driven AUV systems travel at speeds

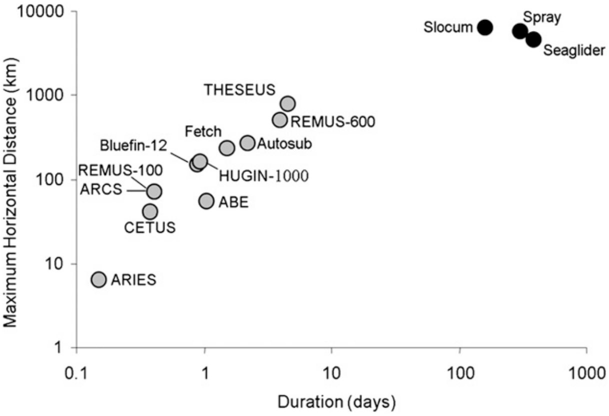

FIG. 2. A sample of current propeller-driven (gray) and gliders (black) AUVs, comparing their maximal horizontal distance and duration on a single charge. The temporal and spatial ranges illustrate the challenge of developing a scalable docking system for these vehicles.

>1 m s^{-1} and offer more systematic sampling capabilities against currents with larger payloads and power capacity for sensors (i.e., acoustics, lasers, etc.; Fig. 1). The propeller systems are further broken down into three primary classes related to their size and based on their uses. The largest vehicle classes are principally used for deep-ocean bottom surveys (Kelley et al. 2005), an intermediate class for shelf and coastal regions (Griffiths et al. 1997; cf. Fernandes et al. 2003), and a smaller class for nearshore applications (Glenn and Schofield 2003; Moline et al. 2005; Robbins et al. 2006; Blackwell et al. 2008; Hibler et al. 2008; Jones et al. 2008; Moline et al. 2009).

For all AUVs, the major operational consideration is the duration of the platform (Fig. 2). This ultimately limits the frequency of use and sustained operations of these systems, as they have historically required human recovery from ships. Developing docking capabilities directly into the fixed infrastructure has long been envisioned as a means for maintaining these systems in the ocean for extremely long periods of time and making them available when needed. Docking provides mobile systems with power, data connectivity with shore, and retasking capabilities. While being frequently highlighted as a need (National Research Council 2003), these docking capabilities remain one of the largest sources of uncertainty in the design of the ocean observatories, ultimately limiting sampling capacity, and making it more difficult to address the science questions highlighted above. In the sections below, we highlight current docking efforts and introduce a new strategy for docking AUVs. A series of field tests are then presented to introduce both the concept and demonstrate the feasibility of this strategy. We conclude with a discussion of the scalability of this approach and implementation within existing ocean observatory initiatives toward assessing the documented changes occurring in the ocean.

2. AUV docking strategies

a. *Automated onboard parking strategies*

Several different docking approaches have been developed that use ‘‘smart’’ propeller-driven vehicles, which essentially park themselves into a fixed system (Stokey et al. 1997; Allen et al. 1998; Singh et al. 2001). There have been two strategies to accomplish this. One approach uses vehicle-mounted hardware to grab a vertical pole or line and thus allow the vehicle to swing with the current. A second approach parks the vehicle in a rigidly moored system. Both of these strategies require the vehicle to locate and navigate to the dock, a method to detect the presence of the vehicle to initiate the docking cycle, and a strategy to attach the vehicle to begin two-way communications and provide power to recharge the batteries. Singh et al. (2001) provide a number of sample decision maps for both the vehicles and docks. These rigid systems can also provide protection for the vehicle while it is docked and may provide protection against biofouling.

These approaches have been successfully demonstrated in the field by a number of groups using various types of AUVs (Stokey et al. 2001; Allen et al. 2006; Singh et al. 2001; more information available online at mbari.org/auv/docking_vehicle.htm). Although these represent major accomplishments, the remaining challenge is that the docking facilities will be difficult to standardize for the wide range of mobile systems being integrated in the ocean observatories (Fig. 1). For example, the two cases referred to above differ in platform design and physical connection. Central to any effort for docking would be to standardize data protocols and some standardization in power transfer. Current data and power connections use either a physical connector or an inductive power transfer and an RF LAN coupling for data communications. These considerations and the development costs will also impact the scalability and prevent deployment of the multiple docking stations needed to provide the required spatial data coverage.

Perhaps the most important issue when considering docking for AUVs is the fact that current systems do not accommodate autonomous gliders, which are currently the most widely deployed mobile autonomous platforms in use in the ocean. Current gliders are constrained to follow a sawtooth pattern when subsurface, which does not facilitate navigation to a particular depth for potential docking. Gliders can, however, both drift on the surface like other AUVs and are also capable of landing

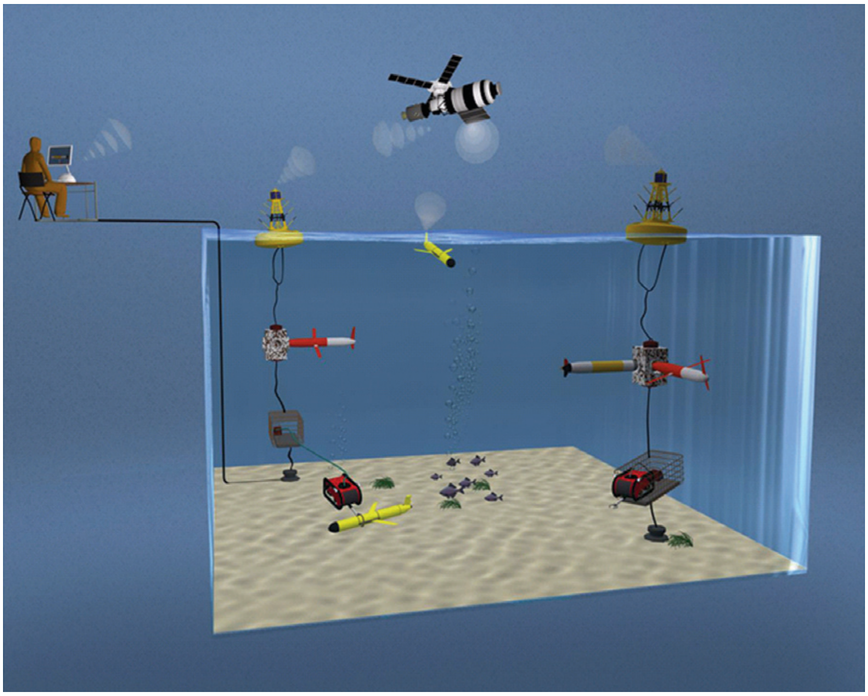

FIG. 3. Conceptual diagram of ROV-enabled docking of AUVs within an ocean observing system. The ROV would be integrated into a cabled node (bottom), providing data and power, or a stand-alone high-powered mooring (surface) providing power with two-way communications via satellite. In either scenario, the remote operator would maneuver the ROV to retrieve the AUV and would be responsible for ensuring the connection to the infrastructure for recharging, data download, and uploading new mission commands. In these scenarios, the AUV could be retrieved either from the surface or from the bottom, depending on the infrastructure.

on the seafloor. These two positions allow a degree of vertical stability for AUVs in ocean environments where new docking approaches may be feasible.

b. Human-in-the-loop docking

We propose an alternative to current docking approaches, which may be applicable to the developing ocean observatories that can provide high bandwidth capabilities and live video feeds. This approach is based on using the video feed to direct small tethered remotely operated vehicles (ROVs) that manually grab the AUV and ''park'' them for power and data connectivity (Fig. 3). Commercially available ROV systems come in a variety of sizes and capabilities, with the costs for many of the smaller systems having decreased significantly. There are several advantages of this ROV–human approach. First, it can be applied to both propeller and glider AUVs and could be scaled to address size and shape differences in AUVs. The requirement for human interaction would only be required for the short periods during the docking procedures and could be done remotely. Having a human in the operational loop would not require a range of advanced behavior routines to be built into the vehicles, and also avoids the issues of standardizing these behaviors across AUV types. Finally, the approach is relatively simple, which is desirable given the highly variable oceanic conditions. It is clear that several aspects of this approach will need to be demonstrated to evaluate feasibility, including the ability to capture an AUV with an ROV operated from a remote setting and developing a standardized method for delivering power and data to the AUVs once connected. In the following section, we describe an effort to demonstrate the feasibility of the former, the use of remote real-time video to enable the capture of an AUV by an ROV after a mission.

3. Field demonstration of ROV-enabled docking

To demonstrate feasibility of a new docking strategy for autonomous mobile platforms, we conducted a series of field tests on 12 June 2006. The tests took place off the California Polytechnic State University's pier facility in San Luis Obispo Bay, California, which acted in this

FIG. 4. Remote real-time capture of a REMUS AUV using a Sebotix ROV. Here, all three images were taken simultaneously with (left) the remote operator, (middle) ROV view of the AUV as it approaches for capture (also seen on operators screen in left), and (right) the aerial view of the ROV approaching the AUV. The effort took place on 11 Jun 2006 from the California Polytechnic State University's pier facility in San Luis Obispo Bay, CA.

demonstration as an offshore cabled node or high-powered mooring (Fig. 3). In collaboration with Seabotix Inc., San Diego, California, we integrated a 10/100 Ethernet card into an LBV150S ROV system, which allowed for standard IP-based communications and interactive control that is portable over the Internet. In addition to controlling the ROV, this upgrade also allowed for streaming video from the ROV's 570 line color camera supported by a 50-W quartz halogen light. Internet communications occurred over a T1 line (1.544 Mbits s^{-1}) with a latency of approximately 2 s in both the refresh rate of the screen and the response time of the controls. This relatively low resolution, low bandwidth, and slow response were chosen to test whether this application was feasible and practical with the potential limiting conditions that might exist with a remote mooring, for example. The AUV used for this demonstration was a REMUS-100 (Moline et al. 2005). The AUV was programmed to conduct a 13-km survey mission in San Luis Obispo Bay. Cal Poly consistently uses the pier facility to deploy and retrieve AUVs without the use of a boat and demonstrate true autonomy in AUV systems (Blackwell et al. 2008; Moline et al. 2009). Using a set of acoustic transponders, the AUV surfaced for retrieval to within 12 m of the goal. After surfacing, the AUV called the base station via Iridium and provided continuous position updates. The ROV was controlled by a single individual 20 km from the ocean at Cal Poly campus without guidance after the ROV was lowered in the water. The ROV pilot was able to view the position information from the AUV and was able to visualize the location relative to the position of the ROV placement (known prior to conducting the AUV mission). With the reference point and the AUV position information, the operator used the heading information from the ROV to locate, connect to, and retrieve the AUV back to the reference point (Fig. 4). Locating the AUV took approximately 4 min. The initial connection between the ROV and AUV took three attempts over a period of 5 min. After the initial test, the ROV was again detached from the AUV, allowing the AUV to drift for a number of minutes before another retrieval attempt. Current speeds during this field test were on the order of 10–15 cm s^{-1} and were not a factor given the 150-m ROV umbilical. This was repeated 4 times with slightly improving results as the remote ROV pilot became more familiar with the control responses. This entire capture demonstration, including the repeated releases and captures, took less than 1 h.

Although this effort clearly revealed the potential of this relatively simple approach, one could imagine scenarios with a fully implemented system where conditions were less ideal than the demonstration here, such as high sea state, strong currents, and increased latency in communications. In all of these scenarios, the largest challenge is achieving a stable and relatively short distance between the AUV and the docking facility (i.e., mooring). To address this distance uncertainty further, data were compiled from 161 REMUS missions conducted from 2001 to 2009 using three navigational approaches and in a host of environmental conditions (Moline et al. 2005; Blackwell et al. 2008; Moline et al. 2009). From these data, the mean distance between the goal endpoint and the actual finishing position was less than 50 m, with the data skewed to the shorter distances (median less than 20 m; Table 1). Eighty of the 161 missions were equal to or less than the distance difference that was used in the demonstration described here. Although not used in most cases here with the REMUS AUV, many existing AUV systems (both propeller driven and gliders) have station-keeping routines, whereby if the AUV drifts a set distance away from the intended location, the vehicle will continue to attempt to eliminate that gap. This would address the maximal distances that were evident from the REMUS dataset (Table 1).

TABLE 1. Statistics of the distances (m) from intended endpoint after each mission. Data were collected from 161 missions of REMUS AUVs from 2001 to 2009. The data are divided into three groups based on the mode of navigation: acoustic network with triangulated positioning, internal compass in combination with surface GPS for navigation, and onboard acoustic homing.

	Acoustic triangulation	Surface GPS	Acoustic homing
No. of missions	93	41	27
Mean (m)	23.87	44.74	25.64
Median (m)	12.70	19.80	13.38
±Std dev	29.66	49.00	36.82
Min (m)	0.06	0.84	1.54
Max (m)	202.17	225.32	175.09

In current Slocum glider operations when vehicles are being recovered, they are flown to a waypoint, which typically has a 1-km watch circle. As recovery teams are approaching the watch circle, the size of the circle is decreased to 500 m. Experience with over 2700 glider days in the water with the glider shows that this approach has been the standard approach for the 160 missions with a 96% success in the last 6 yr (six gliders have been lost at sea). The gliders are able to hold a waypoint less than 500 m, except for conditions where the currents are stronger than 25–30 cm s^{-1}. Based on this experience, if the watch circle were smaller, the gliders would, in most cases, be able to reach their objective within the set watch circle. One added point about gliders is that their increased endurance relative to propeller-driven AUVs decreases the urgency to dock, which allows for undesirable environmental conditions to pass prior to attempting docking.

Acoustic transponders, common in propeller-driven AUVs, are also being incorporated into the gliders, providing the potential to home the glider closer to a docking facility outfitted with a transmitter. Additionally, the development of new glider approaches such as homing on a small watch circle (10–100 m) combined with parking on the seafloor, while possible, has never been attempted. Development of acoustic communications combined with existing behaviors will be critical to developing any docking capability for gliders.

4. Scalability of the ROV approach

This approach has several benefits that take advantage of the ocean observing networks being developed and deployed. The ROV strategy is relatively inexpensive and scalable approach in that it provides a single means for docking the full suite of available AUV platforms, including gliders. The largest cost savings would be in operations and maintenance, by reducing the frequency of ship time required and the personnel time needed for the recovery and deployment of vehicles for sustained periods of time. In addition, by not requiring advanced navigation capabilities to be developed for vehicle docking, these efforts could be focused on enhanced adaptive sampling, cooperative sampling by multiple vehicles, and power and sensor management capabilities (Alliance for Coastal Technologies 2004). Finally, the ROV strategy would also provide additional value-added benefits, such as conducting video inspections of the vehicles, conducting vehicle cleaning to mitigate biofouling of exposed sensors, and provide the same services for other components of the observatory (i.e., mooring, cable, instrumentation, etc.). As mentioned below, scalability of docking systems will be facilitated by standardized data and power transmission for all vehicles classes.

One of the motivations for the initial development of AUV docking was automation and removal of the need for human involvement. With the high cost of AUVs, the complexity of these systems, and the communities growing experience with AUVs, it is highly unlikely, even if docking stations were fully integrated into ocean observatories, that humans would not already be managing these systems during a docking sequence. The assumption that the initial investment in a large number of docks will decrease operational costs in the long term is questionable. It seems logical, therefore, to use an operator already present to facilitate the docking.

With this simple feasibility demonstration, we suggest that all alternative docking approaches be explored and that simple systems take advantage of the human-in-the-loop capability provided by the high-powered cable and mooring technologies. Given the difficulty of continuous operations at sea and the pressing scientific needs the community must address, applying Ockham's razor may be a prudent strategy.

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