# Autonomous Underwater Vehicle Intervention for Advanced Undersea Networks

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***Abstract* - Autonomous Underwater Vehicle Intervention for Advanced Undersea Networks**

***Keywords—Undersea Distributed Networks (UDNs), Autonomous Undersea Vehicle (AUV), Work Class AUVs (WCAUVs), AUV Docking, AUV Intervention, Wave Energy Conversion (WEC), Inductive Connectors, Small Diameter Electro-optic Cables***

## I. INTRODUCTION

Undersea Distributed Networks, UDNs, generally defined as permanent or semi-permanent systems with networks of cables with and without sensors, and that are self-powered or connected to shore with fiber-optic cables, have become a widespread means of acquiring oceanographic and geophysical data. Examples of UDNs are shown in Figures 1 (shore powered) and 2 (self-powered). The areal extent of a UDN can be substantial, measured in tens to hundreds of square kilometers, in water depths to thousands of meters. UDNs have been installed in many parts of the world ocean, as described in Reference [1]. As UDNs have become more complex and sophisticated, the requirements for intervention have likewise increased significantly. Many UDNs are now designed specifically for AUV intervention for maintenance, repair and upgrades, and the UDN components are designed for Autonomous Underwater Vehicle (AUV) interfaces.


Fig. 1. Shore Powered Undersea Distributed Network

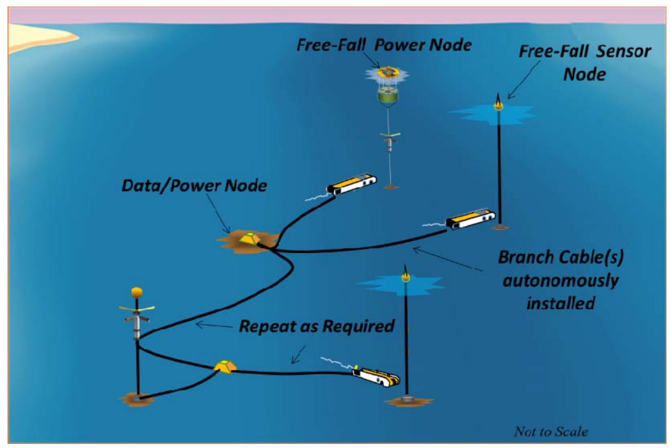


Fig. 2. Operational Concept for Self-Powered UDN

## II. WORK CLASS AUVs

Work Class AUVs (WCAUVs) typically have five- or six-degree-of-freedom maneuverability and fully stable auto-hover capabilities (often in any attitude). Their rectilinear form factor allows them to add specialized mission-specific work packages ("skids") as well as full-function manipulator arms and hands. They can be fitted with a variety of tools such as seafloor geotechnical tools, inspection sensors and specialized tools for working on UDN systems.. The skids are typically self-powered with their own batteries, and are controlled through the AUV control system. As yet, there are few WCAUVs in operation. An example of a WCAUV is the SAAB Sabertooth, shown in Figure 3, below. Figure 3 shows examples of the Sabertooth work-class vehicle with different work packages for intervention tasks. The WCAUVs can hold station in more or less arbitrary current directions with velocities up to about two knots. They have a payload capability of from a few hundred kilograms to substantially more (thousand kg). The stable hovering capability is critical to performing intervention work tasks. It is this capability that largely distinguishes WCAUVs from search and survey AUVs. WCAUVs are designed to operate while anchored to the work site using a manipulator or other means, or in "free-flight' mode. Figure 4 is the Subsea 7 Autonomous Inspection Vehicle. This vehicle is designed for

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long-term bottom-resident functionality for inspection and light work tasks for the oil and gas industry. Both the SAAB and Subsea 7 vehicles are designed to operate with a docking station for recharge and data transfer. The SAAB system is shown in Figure 5, and the Subsea 7 system is shown in Figure 6.

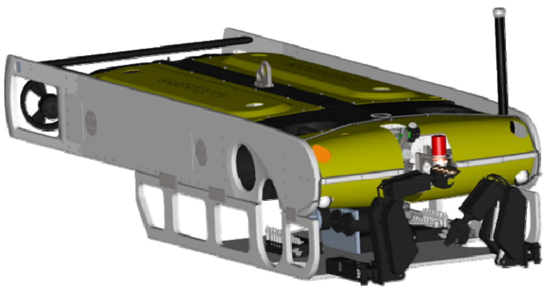

Fig. 3A. WCAUV with Manipulator **Skid** (image courtesy of SAAB)

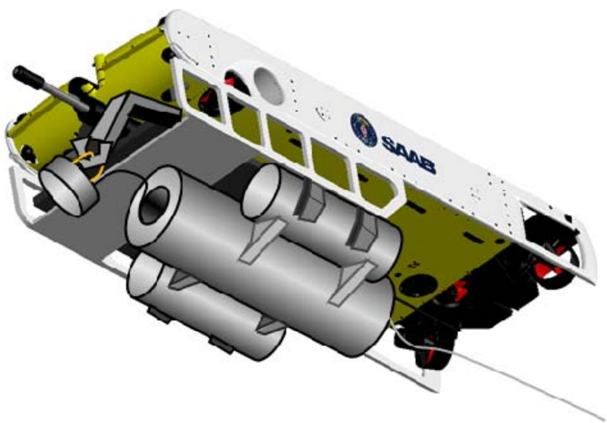


Figure 3B. WCAUV with Cable Dispenser Skid


Fig. 4. Subsea 7 Autonomous Vehicle (image courtesy of Subsea 7)

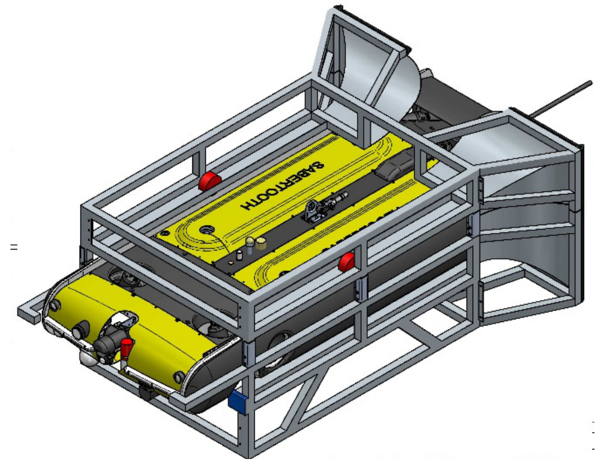


Fig. 5. Sabertooth Docking Station (image courtesy of SAAB)


Fig. 6. Subsea 7 AIV Docking Station (image courtesy of Subsea 7)

## III. INTERVENTION TASKS

Intervention, as used here, includes such actions as inspection; installation, repair or replacement of sensors; replacement or recharge of power supplies; laying cables; repair or replacement of faulted cables; placement of objects on the seafloor, object recognition and recovery; and data recovery. To take best advantage of AUV intervention capabilities, UDNs will require modular and AUV-friendly architectures. An analogy is the design of equipment for the Space Station, where equipment is designed for easy removal and plug-in replacement. For some components, the connection might be integral to the components. For others, the connection might be with a pigtail electrical, electro-optical or optical cable. An AUVs intervention tasks might require free-floating ("free-flight") operation, or tasks might require the

AUV to anchor to the UDN element. The wide range of possible AUV intervention tasks results in several broad classes of possible interfaces between the AUVs and UDN hardware, modular units and connections. The classes of interfaces are more broadly stated as insertion/withdrawal (connectors, plug-and-play components); torque/rotation (operating valves or switches); push/pull (open hatches to access components); combinations of these; and probably others. These are all physical interfaces, some of which enable electrical or optical interfaces.

Many of these tasks have elements in common as described above. Each of these tasks typically requires a specialized configuration of the WCAUV. As discussed in (Meggitt, et al. 2016), extended development of AUV intervention capabilities for operations with UDNs requires development of standardized interfaces for tools and UDN components.

### *A. INTERVENTION SCENARIOS*

Figure 7 (from Meggitt, et al, 2016) show two types of intervention scenarios.

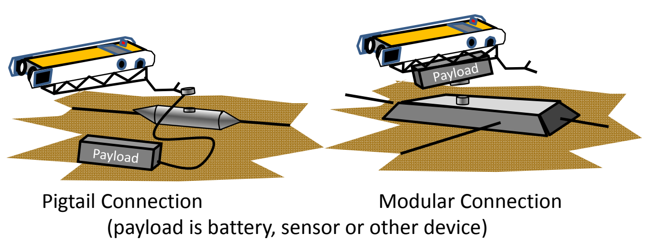


Fig. 7. Intervention Scenarios

The image on the left shows a Pigtail Cable Connection. In this scenario, the replacement component is placed on the seafloor or structure adjacent to the item to be replaced or bypassed. The new component is then connected to the in situ unit by a standardized connector on the end of a pigtail cable. As discussed in Meggitt, et al. (2016), there is a need for standardizing interfaces between AUVs and UDNs to facilitate AUV intervention. The pigtail-component connection configuration is more appropriate when the in situ component design is not compatible with a modular interface. This might be the case for UDN elements such as complex sensor or acoustic arrays, or other elements with shape or size constraints. The pigtail interface imposes the minimum requirements on the design of the originally-installed hardware, and allows maximum flexibility in the design of any replacement components to facilitate AUV intervention, so they can be easier for the AUV to handle. The computer hardware analogy here would be an external hard drive connected to a computer by a short USB pigtail cable.

For Modular Unit Connections, the replacement component and its associated connections for power, and electrical and optical data exchange are a single element. A simple computer hardware analogy would be a USB drive, in which the item to be connected (a memory chip) and the connection hardware (a USB connector) are a single package. The configuration is mechanically simple, but it requires that the entire unit be something can be handled by the AUV and, of course is physically, electrically and optically compatible with the component to which it is to be connected. An example might be the modular replacement of a camera or oceanographic sensor. The connecting element itself might either be a direct-contact connection (like the USB port), or a contactless connection combining inductive electrical charging with an optical or acoustic data link.

Note that in either case, the device that performs the electrical and optical interface (the “connector”) performs the same functions and should be standardized at that level. Both power and optical data formats can and should be standardized. In addition, even with an inductive (contactless) connection; there are some physical constraints on alignment of the two connector halves, which should be standardized.

Close inspection, for condition assessment, for example, presents another intervention scenario well-suited to WCAUV operations. A development objective for both the Sabertooth and the AIV was the ability to document the condition of seabed infrastructure. The stability of both of these vehicles is essential to high-resolution imaging of seabed equipment or features. Imaging is required in low-visibility as well as high-visibility conditions in relatively clear water, so ultra-high resolution acoustic imagers are an important addition to optical sensors..Future Developments

Several ongoing developments are enabling technologies for AUV intervention for UDNs.

The development of contactless power and data connectors has the potential to simplify UDN design constraints substantially. Although current designs result in some loss of efficiency in power transfer, the gains in simplification of intervention operations is likely a very worthwhile trade. Figure 8 shows a concept for a 5kW, 1Gbps contactless underwater connector. The connector is designed for UDN applications with connection by an AUV that carries the electro-optic cable spool (Figure 3B). The technology embodied in this design has shown power transfer efficiencies of 95%.

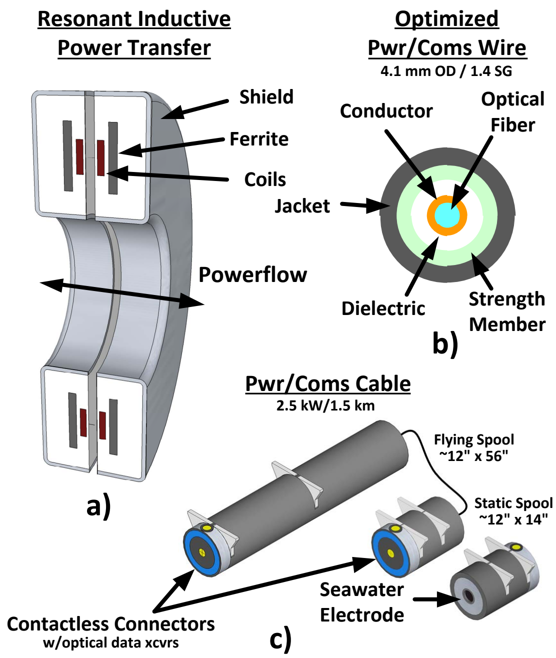


Fig. 8. Contactless Connector Concept (image courtesy of General Atomics)

Several previous programs have deployed cables from AUVs or ROVs, dating from at least the mid-1990's. These programs included among others ARIADNE, THESEUS, Advanced Deployable System (ADS), NEREUS, and others. Torpedoes have used small-diameter wire or fibers for guidance and control for decades. The AUV and ROV deployed cables have ranged from essentially bare, buffered fiber to fibers in small-diameter steel tubes or with Kevlar jackets. Cables have been deployed from spools slung under ROVs or AUVs. More typically, the cables are wound into inside- or outside-wind packs, often with easily stripped binders for control of the payout rate. In essentially all of these previous projects the cable has a fixed starting end and a free end, sometimes with sensors at locations along the cable or at the end. In addition to this kind of configuration, a typical UDN cable deployment will also have a fixed starting end that might require connection by the AUV. The other end likely will have a connector termination that requires manipulation to connect to another element of the UDN. The cable package and interface to the AUV require careful design and attention to the interfaces between the cable and UDN at both ends of the cable. As noted above, development of contactless connectors will substantially simplify this kind of operation.

As computer processors become more powerful and at the same time smaller, and programmers become more sophisticated in taking advantage of the available, computing power, adaptive 'smart" decision-making programming that utilizes data from visual and/or ultra-high resolution acoustic imagery (e.g., machine vision) will increase the capabilities of AUVs to conduct complex intervention functions and to operate in complex, crowded environments. Ultra-high resolution acoustic imagers significantly improve the ability of AUVs to "see" in limited visibility environments and can provide inputs for enhanced image recognition capabilities. Extension of machine vision capabilities can be extended to AUV inspection and intervention.

Many, perhaps most, intervention operations require manipulation. This level of intervention manipulation is more sensitive than typical oil and gas operations, and calls for more dexterity and force sensitivity than the current generation of hydraulic work manipulators. The development of highly sensitive, compact force feedback manipulators is another enabling technology that will greatly facilitate AUV intervention. Manipulator development has emphasized hydraulic systems for ROVs. These manipulators are operated from the surface, and feature substantial power and a high ratio of force capability to weight. Hydraulic manipulators are relatively easy to pressure compensate for operations at depth. For electrically-powered AUVs, however, hydraulic manipulators have several disadvantages. They require a hydraulic power unit, have complex valving, and there is some risk of environmental contamination from hydraulic fluid, although this has been mitigated by the development of environmentally-compatible fluids. Because of their complexity, hydraulic manipulators are typically quite expensive. Electric manipulators feature smaller output power coupled with higher precision, and are well suited to intervention tasks for AUVs. In addition, electric manipulators provide better overall system efficiency, a substantial consideration for battery-powered AUVs. It is interesting to speculate how the dramatic developments in human prosthetics might benefit the development of high-precision underwater manipulators.

The development of higher energy-capacity, longer duration batteries is a key development objective for AUV technology. There are several development efforts underway, generally based on a lithium chemistry. In addition, several projects are seeking to improve the safety of lithium-based batteries. The ability to recharge batteries in-situ is a critical requirement for extended AUV operations with UDNs. Both the SAAB Sabertooth and the SubSea 7 AIV are designed for in-situ inductive recharge. The plans for several UDNs (e.g., Regional Scale Nodes) include the addition of seafloor recharging stations. AUV intervention operations with forward-deployed UDNs are likely to require mid-water docking and recharge stations, which present an interesting set of both docking and charging challenges. Unless they are shore-connected, these systems will require some forward-deployed source of energy. This would probably be renewable, likely wave energy, solar or some combination that can meet generation, survivability and observability requirements. One possibility is a variation of the Lifesaver Energy Platform, shown in Figure 9, currently under test at the Navy Wave Energy Test Site off Kaneohe, Hawaii. This technology is scalable for a range of generator outputs, and has shown survivability in up to 10 meter wave conditions.


Fig. 9. Lifesaver Wave Energy Platform

A critical requirement for AUV intervention operations for UDNs is the ability of the AUV to home on work site locations and docking/recharge stations. Homing typically has several phases that utilize different technologies. The general location of the target or homing site is usually programmed into the AUV guidance and control system. Once the AUV is in the vicinity of the target location (autonomously), an acoustic beacon and transponder (usually an Ultrashort Baseline system) gives guidance information to the AUV. The target often has sonar reflectors to provide additional positional information using the AUV's own sonar. The terminal guidance can be ultra-high resolution acoustics or optical or both. The application of image processing and machine vision technology (including Automatic Target Recognition) is improving the ability of AUVs to home in on work site locations. As an example of homing to a docking station, the SAAB Sabertooth AUV utilizes a fully autonomous approach to docking with TRANSIT, APPROACH and DOCKING phases. The TRANSIT phase utilizes the on-board autonomy world model, which includes mission details and approximate location of the dock. This on-board autonomy can be used to ensure that a decision can be made to initiate docking using approach mission parameters (e.g. mission progress, battery remaining, location) and that a suitable trajectory is planned towards the dock location.

During the APPROACH phase, the system uses a "smart dock" that incorporates a USBL beacon capable of providing relative position (range/bearing), the current docking orientation (heading) and system status (clear for dock) to the AUV. This will be used as the primary source of information to update the accuracy of the dock location as the AUV closes on the general location (approx. 1km).

In the final docking phase, a forward-looking sonar system is used with Automatic Target Recognition. Small sonar reflectors placed at suitable points around the dock entrance can be used for more precise identification of the location and orientation of the dock entrance from a range of about 50 meters. For non-hover capable vehicles, the suggested approach strategy is a "fly-by" maneuver to identify and precisely locate the dock, before circling back around and commencing the final docking maneuver. This is suggested due to the difficulty of performing late stage corrections, particularly lateral, with a torpedo-shaped vehicle that will essentially "skid" sideways. This docking technique, shown in the Fig. 10 below, is broadly similar to the typical aircraft landing pattern. A similar methodology is used for detection, localization and terminal homing for work site targets.

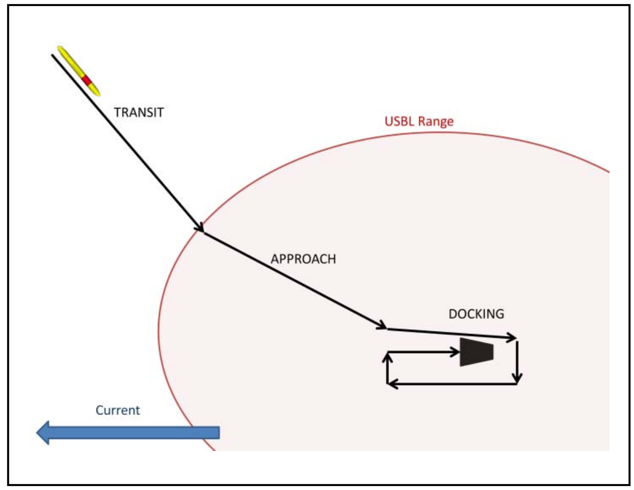


Fig. 10. Typical Landing/Docking Approach Pattern

Conclusions

Intervention by AUVs has the potential to significantly increase the capabilities available to UDN designers and installers. The abilities of AUVs to perform complex intervention operations autonomously depends on the more or less simultaneous development of several key, interrelated technologies. These include:

- Contactless electro-optical connectors
- Task-specific, self-powered work packages
- Lightweight, high-precision manipulators
- Advanced battery technologies with enhanced safety
- Bottom and midwater docking stations
- In-situ recharge and data transfer capabilities
- Enhanced high-resolution imaging systems for low-visibility conditions
- Smarter autonomy using machine vision for close-in intervention operations

[1] Meggitt (2016): Development of Standards for Underwater Distributed Architectures; Meggitt, Dallas; Wilson, Jeffrey; McAlister, Daniel; Henson, Joshua; Oceans '16 Shanghai, April 10-13, 2016

[2] Ridao (2014): Intervention AUVs: The Next Challenge; Ridao, Pere; Marc Carreras; David Ribas; Pedro J. Sanz; Gabriel Oliver; Preprints of the 19th World Congress of The International Federation of Automatic Control' Cape Town, South Africa. August 24-29, 2014