Reimagining Autonomous Underwater Vehicle (AUV) Charging Stations with Wave Energy

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ABSTRACT

The vast capabilities of autonomous underwater vehicles (AUVs)—such as in assisting scientific research, conducting military tasks, and repairing oil pipelines—are limited by high operating costs and the relative inaccessibility of power in the open ocean. Wave powered AUV charging stations may address these issues. With projected increases in usage of AUVs globally in the next five years, AUV charging stations can enable less expensive and longer AUV missions. This paper summarizes the design process and investigates the feasibility of a wave powered, mobile AUV charging station, including the choice of a wave energy converter and AUV docking station as well as the ability to integrate the charging station with an autonomous surface vehicle. The charging station proposed in this paper meets many different commercial, scientific, and defense needs, including continuous power availability, data transmission capabilities, and mobility. It will be positioned as a hub for AUV operations, enabling missions to run autonomously with no support ship. The potential market for this design is very promising, with an estimated $1.64 million market size just for AUV technologies by 2025.

INTRODUCTION

The global autonomous underwater vehicle (AUV) market is expected to grow from $638 million in 2020 to $1.638 billion by 2025 [1]. The military and defense sector currently holds and is expected to continue holding the largest market share of the AUV industry. Within these sectors, AUVs can be used in mine countermeasures, anti-submarine warfare, reconnaissance, and force protection; each of these areas are projected to grow significantly in the next few years.[1]

In this paper, we propose a model closed loop, autonomous system that would enable AUVs to operate for long durations without human intervention—including recharging and data collection—over large swaths of oceanic territory. Existing AUVs are limited by power and data capacity and must return to ship or shore for battery recharge and data collection. An emerging technology, underwater docking stations, helps AUVs to recharge and store extra data underwater, but is highly limited by its battery capacity and maintenance requirements.[2] However, our proposed solution combines a wave energy converter (WEC) and an associated AUV docking station into an autonomous platform that eliminates the need for manual operation.

DESIGN PROCESS

The following design consists of three primary subsystems: the WEC for power generation, an autonomous surface vehicle (ASV) that acts as both a mobile central node and command module, and a docking station for power and data transmission to an AUV.

1. Wave Energy Converter

The WEC is the primary power generator. We chose to use a heaving point absorber design, which requires an absorber at the top and an anchor at the bottom. Instead of using a counterweight to anchor the absorber, the absorber in our design uses the relative motion between the ASV and a sea anchor, caused by waves, to pull a spring-loaded mooring line spool that spins a rotary generator. The combination of an ASV and WECs uses few moving parts exposed to seawater, and the point absorber design has a high power absorption to surface profile area ratio while still maintaining a mobile ASV capability. Using the ASV as the absorber also improves the system's stealthiness, which is vital to defense customers—ASVs are already used in covert operations.[3]

1.1. Heaving Point Absorber

Among the six types of WECs (point absorbers, terminators, attenuators, oscillating wave surge, submerged pressure differential, and rotating mass devices), we narrowed down our choices to the heaving point absorber and attenuator designs because of their relatively high capture width ratio andCWR efficiency (capture width divided by a characteristic dimension of each WEC). CWR is considered to be equivalent to the hydrodynamic efficiency, which best reflects the hydrodynamic performance of WECs. Ultimately, the heaving point absorber offered the greatest benefits for planned uses due to its small size, flexility, minimum maintenance requirements, and high CWR efficiency.[2] With the ASV acting as a buoy for the point absorber, the WEC and ASV can be linked under the same system.

1.2. Sea Anchor

Because the usage of a traditional heavy counterweight or anchor would not be conducive to the deployment of a mobile system, we used a sea anchor, or para-anchor, to provide the reaction force for the WEC. The sea anchor is an underwater, inverted

Figure 1: Example diagram of an off-the-shelf para-anchor.[4]

parachute that uses water pressure to stabilize a sea vessel. It provides a counterforce to waves lifting up the ASV by pulling a cord linked to the spring loaded mooring line spool. While the ASV will move with the movement of the water's surface, the small amount of power lost to sea-anchor movement is minimal in comparison to the amount of power and space necessary for a full anchor and winch to secure the WEC.

2. Autonomous Surface Vehicle

The ASV is the central node of our system. It connects the WEC to the docking station and provides a platform for electronics and system control. The ASV houses the WEC rotary generator, the underwater docking station, and battery power storage. The ASV also contains other electronics platforms for data collection and transmission. Motors and winches inside of the ASV will lower elements of the WEC and docking station, and two additional motors will power the propulsion system. Solar panels on the top of the ASV provide an alternative power source in the case of low wave activity.

2.1. Hull Structure

When selecting the hull design of the ASV, our two primary choices were a monohull or catamaran structure. Initially, the monohull structure appeared best because of its simplicity and prevalence, but the catamaran hull's greater stability and buoyancy outweighed the drawback of its complexity. These features help the WEC ride higher above the waves and capture energy that would otherwise be lost to unstable motions. The dual hulls also create less drag, which reduces energy used to maneuver; having two propellers further apart limits the need for a rudder, which would be another point of possible failure due to frequent fracture. Catamarans also provide more space than monohulls, which is beneficial for storing additional equipment on an AUV.[7]

2.2. Mobility

AUVs across many industries prioritize the need to cross vast distances across the ocean rather than maintenance and surveillance around a specific area.[8] The charging station must travel with the AUV to increase its range and operational capability. Through a careful selection of the WEC, more power can be produced with the proposed configuration than needed by two operating AUVs. While an additional motor creates additional power demand and increases design complexity, it does not outweigh the benefits of creating a near infinite range for the AUV.

2.3 Solar Power

Solar panels placed across the surface of the ASV can act as a secondary source of power, primarily for when the wave height does not create optimal power generation through the WEC. Based on a solar panel efficiency of 20 percent and a surface area of 1 m2, 200 W and 1.6 kWh of energy per day can be produced (assuming 8 hours of sunlight).[9]

2.4 Power Storage

Lithium ion batteries charged by both the WEC and solar panels will be the primary power source. Using lithium ion batteries was a natural choice given their prevalence and relatively high power density (above 200 Wh/kg) in comparison to the lead acid battery (under 50 Wh/kg).[10] The batteries will be placed in two groups aboard the catamaran, one at the bottom of each hull. This positioning would provide greater stability and safety for the craft because the batteries weight will be focused to the lowest and widest possible locations in the craft. The ability to separate the battery into two sections provides redundancy in the case of failure within one battery compartment. Based on current battery standards, about 20 kWh of storage capability will be introduced onboard, which is

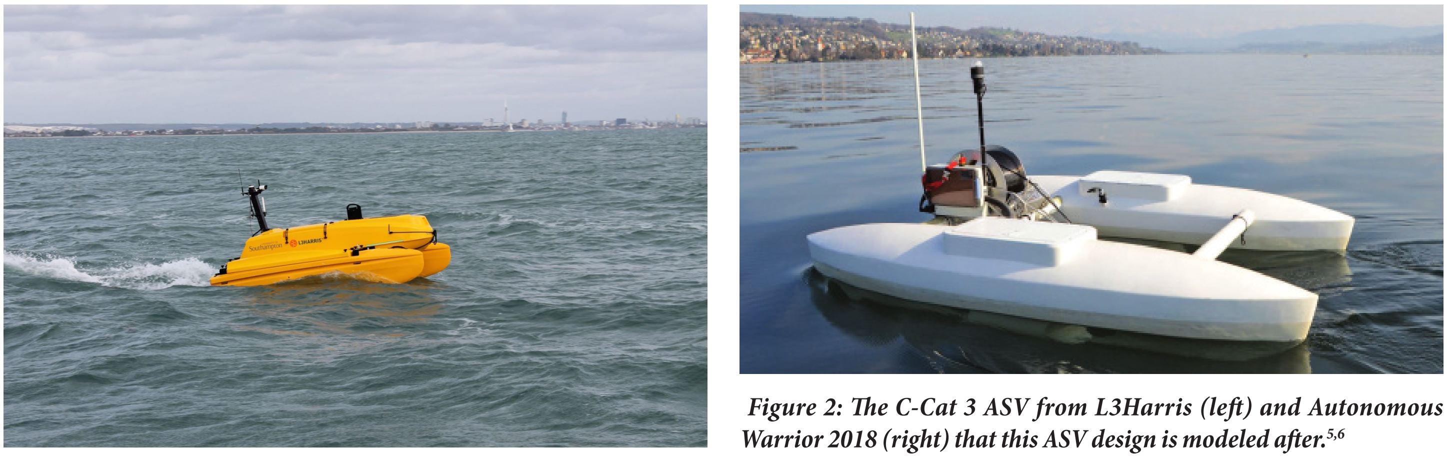

Figure 2: The C-Cat 3 ASV from L3Harris (left) and Autonomous Warrior 2018 (right) that this ASV design is modeled after.[5,6]

enough energy to charge an AUV and move the ASV.[11]

2.5. Data Transmission (AUV-ASV-Satellite/Shore)

Traditional AUVs and remote research sites will often use hard drives or other data storage devices to maintain recorded and obtained data, with manual means of data retrieval. However, this model presents three primary issues: the possibility of data loss through storage failure; inaccessibility, where access to a remote site is difficult and costly; and untimeliness of data availability. To counteract these limitations, data will be directly and instantaneously transmitted through a satellite to the consumer, negating all three issues with storing data aboard the system. Reliable hard drives are available as backups when satellite communication is lost.

3. Docking Station

The docking station provides a secure power and data connection to an AUV. The docking station uses a drop cord, consisting of a cord attached to the ASV with a winch that can be raised and lowered to any desired depth. The cord would transfer power from the ASV to the AUV and collect data from the AUV. The ability of an AUV to be able to stay beneath the surface saves time and money during operational periods. Another concern is the growth and buildup of marine biomass—including barnacles, algae, and tubeworms—creating an obstruction between the docking station and the AUV's contact points. Maintaining an operational depth below 300m prevents the buildup of such biomass. Finally, our design creates a universal docking station, so that customers who may need a wide variety of differently sized or shaped AUVs can select their systems based solely on their mission tasks instead of the capabilities of the charging station.

3.1. Drop Cord

There are two main types of AUV docking stations: cone systems and wire latching systems. A cone system is composed of a horizontal cylindrical housing and a funnel cone for the AUV to drive into.[12] After the vehicle is homed inside of the cylinder, there are usually some mechanisms, such as clamps, to secure the AUV. Either wet-mateable or inductive charging could be used. Although the cone system provides high protection for the vehicle and high efficiency of charging and data transmission, it has a big flaw: the shape of the cone and size of the cylinder varies greatly with the type of AUV used in the mission. It also requires extreme precision for homing because of the limited size of the inner cylinder.

The wire latching system, in contrast, is a design that can charge any AUV regardless of its shape or size. The most developed design comes from a collaboration between the MIT Sea Grant Laboratory and the Woods Hole Oceanographic Institute's Autonomous Ocean Sampling Network (AOSN) Dock. This docking station is a vertical latching system composed of a V-shaped titanium latch along a spring-loaded capture bar secured on the nose of the vehicle. In order to latch to the station, the AUV drives into the long vertical docking pole and pushes the capture bar aside with its forward momentum. The latching operation is entirely passive, which allows the AUV to be kept at the station for safety even during a power outage. In order to undock, the vehicle releases the capture bar through a rotary actuator and withdraws from the pole. AOSN was designed to provide both charging and data transmission wirelessly via conducting cores that are built on the AUV nose's underside and on the lower dock carriage's upper side; the core that is on the AUV can be folded until it needs to be employed. The docking process is accomplished via an ultra-short baseline system on the vehicle and a 2 kHz acoustic beacon on the hub. After that, the two conducting cores are aligned as the lower carriage of the dock is driven up so that the AUV is forced to stay tight between the two carriages as well as to the conducting pads on the carriages. Meanwhile the conducting cords are also tightly secured.[13]

Figure 3: The AOSN docking components on the deck (left) and an omnidirectional approach to docking (right).[14,15]

While latching designs like the AOSN dock do not provide AUVs full-body protection like the funnel designs do, they keep the AUV very stable and, through their passive connective mechanism, protect it from drifting away. The latching mechanism can be easily installed on any AUV nose and allows the AUV to home from any direction; it serves as a truly universal docking station for any market.

In addition, housed dock electronics include a Long BaseLine transponder for acoustic navigation and a utility acoustic modem for communication with the AUV. A homing beacon, located above the docking pole, signals the AUV's ultrashort baseline homing system. Dock sensors include an acoustic Doppler velocimeter to measure currents, a Seabird SBE 38 temperature sensor, a Paroscientific pressure sensor to monitor total depth, and dock carriage position switches to determine dock status.[3]

As in our design, the key parts of the AOSN docking station will be implemented (electronics, movable carriages, conducting cores, and conducting pads). Note in Figure 4, the positions of conducting cores and the two carriages are flipped but their functions remain the same.

3.2. Power Transmission

The three sections of an AUV are connected via power transmission. An electrical cable is sufficient to transmit power between the ASV and the docking station. However, power transmission from the docking station to an AUV will require a non-permanent connection. There are two solutions: a direct, wet-mateable connection or inductive charging. The wet-mateable connection between the AUV and docking station provides a higher rate of power transmission compared to inductive charging, but requires the AUV to be positioned extremely precisely relative to the docking station. Specifically, a wet-mateable solution would directly connect the AUV to the docking station through metal contacts, such as a plug, while inductive charging would only require the AUV to be close to the docking station for power transmission. Inductive charging tolerates a margin of error, minimizes electrical faults, generates little heat, and is more durable. Thus, inductive charging is preferable for power transmission between the AUV and docking station. While its primary drawback is power loss, A 2019 study showed that the power loss was not significant enough to create a problem.[10]

The AC voltage generated by the wave converter is rectified to DC voltage because of DC power's superior transmission capabilities in salty ocean water; it does not need an additional cable to attune to the negative polarity of ocean water. In contrast, AC power requires three-phase cables.[12] This current will run from the WEC to the battery and then down to the docking station where the AUVs will be charged.

3.3. Data Transmission (ASV-AUV)

While the optimal choice for data transmission between the AUV and docking station would be a direct connection, the stringent requirements for a direct connection would limit the capability of the docking station. Thus, the design includes a wireless connection through radio waves as both acoustic and optical methods are not suitable for data transmission. Real time transmission and satellite communications with the land can be achieved with an antenna on the ASV. Radio waves would work properly at 315Mhz or 433Mhz.

4. Final Conceptual Design

By incorporating three different subsystems of mobile ASV, heaving point absorber WEC, and drop cord charger, this AUV design is a new system that uses wave energy to power the growing AUV industry.

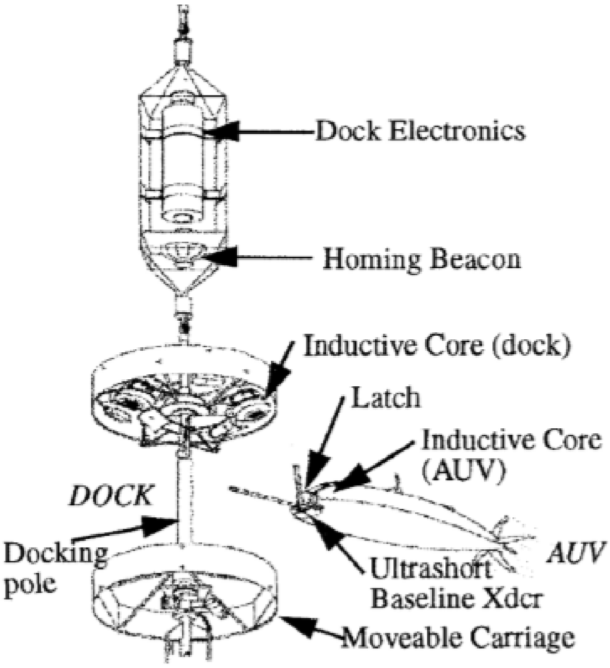

Figure 4: Labeled view of the AOSN omnidirectional docking station with AUV latching system.[14]

Property	Acoustic	Optical	RF
Bandwidth	~kpbs	~gpbs	~Mpbs
Range	kms	~100 m	~10 m
Speed	1500 m/s	$2.2 \cdot 10^8$ m/s	$2.2 \cdot 10^8$ m/s

Table 1: Characteristics of underwater communication (Alex Immas, personal communication).

CONCLUSION

With more than eighty percent of the ocean unexplored and untapped, more AUVs could be deployed in the future and this will require an autonomous powering and data transmission system. This design could replace traditional fixed-point WECs to create a new future. In addition, instead of building a separate body for the WEC or an expensive system dedicated to just one specific AUV, this proposed design has a unified and simplified structure that is created to achieve the needs of multiple consumers by using the ASV as a heaving body. Further actions are needed for building a physical prototype and validating the theoretical knowledge presented.

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APPENDIX

The appendix to this article may be found online by navigating to: https://escholarship.org/uc/our_bsj/

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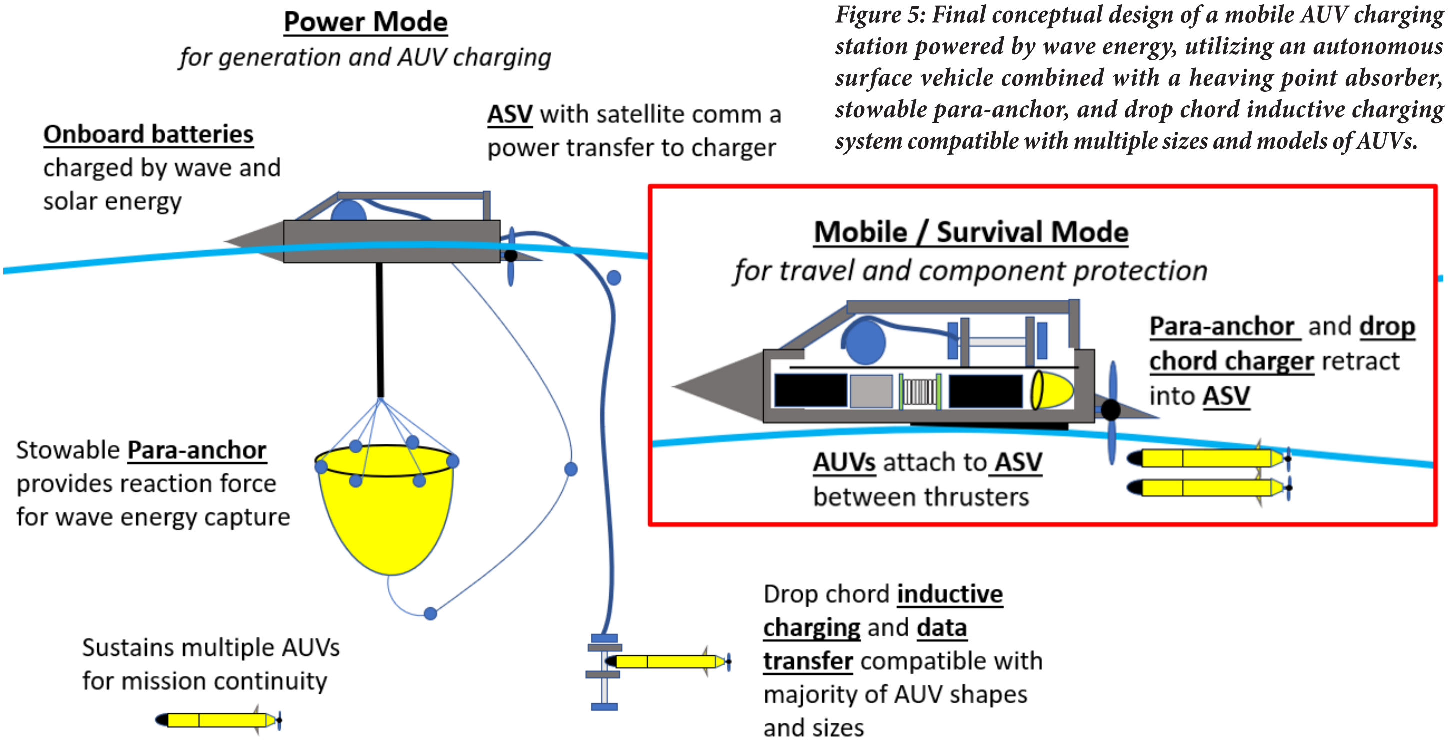

Figure 5: Final conceptual design of a mobile AUV charging station powered by wave energy, utilizing an autonomous surface vehicle combined with a heaving point absorber, stowable para-anchor, and drop chord inductive charging system compatible with multiple sizes and models of AUVs.

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