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Powering the Blue Economy: A Survey of Station-Keeping Methods for Mooringless Platforms

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List of Acronyms

AUV	autonomous underwater vehicles
EM-APEX	Electro-Magnetic Autonomous Profiling EXplorer
FAD	fish aggregating devices
FIT	failure in time
FOWT	floating offshore wind turbine
GPS	global positioning system
HYCOM	Hybrid Coordinate Ocean Model
MRE	marine renewable energy
NDBC	National Data Buoy Center
NOAA	National Oceanic and Atmospheric Administration
OWC	oscillating water column
PBE	Powering the Blue Economy
PID	proportional-integral-derivative
PTO	power take-off
PV	photovoltaics
ROMS	Regional Ocean Monitoring System
ROV	remotely operated vehicles
SBIR	Small Business Innovation Research
SLOT	Submarine-Launched One-Way Transmitter or Tactical
STTR	Small Business Technology Transfer
TEC	tidal energy converter
USV	unoccupied surface vehicle
UUV	unoccupied underwater vehicle
VLFS	Very Large Floating Structures
WEC	wave energy converter
WTS	Wave Turbine System

Executive Summary

The term "ocean platform" is used to reference everything from stationary, typically moored, buoys to mobile water vehicles, whether they operate on the ocean's surface or underwater. For certain applications for which relatively stationary station-keeping conditions are desired, the use of mooring systems is not always a viable alternative either for economic, environmental, regulatory, or otherwise practical reasons, or a combination thereof, (e.g., short deployments, sensitive ecosystems, very deep project sites). Maintaining a platform at a single waypoint or reference location without being moored would require additional control systems and a power source to counteract the drift forces that would naturally displace it.

Mobile platforms, which are usually untethered except for remotely operated vehicles, typically require energy input to power their station-keeping capabilities so that they hold or control their location in the ocean. Currently, most of these platforms use combustion engines or batteries for this purpose, which, depending on the specific systems, may be costly, pollute the environment, or create limitations on the length of the deployment. However, powering this kind of platforms with surrounding renewable resources (waves, currents, winds, or sun) has been identified as a promising solution to expand their application.

The intent of this report is to investigate station-keeping methods for various ocean platforms that are not moored or otherwise anchored to the ocean floor, or another platform or vessel, paying particular interest to technologies that use marine renewable resources to power their operation, because that is of particular interest to the U.S. Department of Energy's Powering the Blue Economy (PBE) initiative.

As a first step, 72 articles and technical reports related to mooringless station-keeping methods were collected for review. The preliminary literature review provided a broad overview of common themes across the literature from which a descriptive methodology for analyzing various platforms was developed. That is, station-keeping methods are henceforth categorized based on their:

- **predominant energy source and consumption**, which can be either "renewable" if the platform operates primarily using renewable energy resources, "nonrenewable" if the platform operates primarily using nonrenewable energy resources, or "hybrid" if the platform uses renewable and nonrenewable resources equally; and
- **localization strategy**, which can either be "drift reduction" if a platform is allowed to move relatively freely but has a system in place to reduce drift, "path-planning" if the platform is designed to follow an intended course, or "waypoint-holding" if the platform remains at a given location, perhaps with some allowance to drift within a watch-circle (imaginary circular boundary around the anchor point) similar to a moored platform.

In addition, for further analysis platform types are segregated into the following groups: buoys, surface drifters, and unoccupied surface vehicles (USVs); offshore renewable energy systems; and unoccupied underwater vehicles (UUVs).

Buoys, Surface Drifters, and Unoccupied Surface Vehicles

Buoys are buoyant objects that sit on the water's surface and are traditionally moored. They are used for a variety of applications including marine science, maritime navigation, meteorology, fishing, offshore energy, or military and defense applications. Mooringless buoys use a waypoint-holding strategy and are sometimes described as being "virtually moored." Examples of mooringless buoys include a floating device conceptualized by Pohang University of Science and Technology with a submerged wave-induced turbine and a propulsion unit; a buoy designed by L3Harris that maintains its position using nonrenewable energy via a combined diesel-electric power system; and a buoy under development by the U.S. Navy that has a hybrid energy source combining solar, fuel cells and kinetic energy.

Surface drifters are also buoyant objects, but they are free to drift with prevailing waves and currents. They are typically used for ocean science applications and are best suited for sampling the ocean over larger spatial scales. Their predominant energy source is nonrenewable (they are usually equipped with alkaline batteries to power onboard instrumentation) and they use a drift-reduction strategy (they are tethered to drogues to avoid abrupt chances in location).

USVs are self-propelled mobile platforms limited to surface operations for a variety of ocean science, security, and military, and industrial applications. Many USVs on the market use nonrenewable energy (e.g., diesel, batteries, gasoline) for station-keeping and powering instrumentation, for examples vehicles manufactured by Marine Advanced Robotics, Kongsberg, and L3Harris. An example of a hybrid powered USV is a kayak developed at the Massachusetts Institute of Technology that uses a solar rechargeable battery to power instrumentation and a diesel generator to power an electric motor. Lastly, there are also examples of USVs powered by renewable energy, most of which use a combination of energy sources. For propulsion, the Wave Glider and the Autonaut use wave energy, and the Saildrone uses wind energy; all three devices use battery/solar panels to power the onboard sensors and communications instruments.

Offshore Renewable Energy Systems

Offshore renewable energy devices are designed to harvest offshore renewable resources (waves, tides, and winds). Applications for these platforms vary depending on their size and whether they are used individually or as part of an array. An array of offshore devices would be able to supply grid scale electricity on the scale of 3–15 MW. Small devices, rated up to 10 kW, could instead be used to power oceanographic sensors, mobile aquaculture operations, communications/security activities, or they could be used as docking and charging stations.

Wave Energy Converters (WECs) extract energy from ocean waves. Most WEC archetypes are envisioned to have mooring systems, and energy harvesting is achieved by exploiting the differential motion of passing waves relative to the constrained devices. An alternative system that does not require constraints involves an internal mass that resists the movement of an enclosing hull to produce power. One such platform is currently under development by Ocean Power Technologies for the U.S. Navy. Another mooringless design proposed by researchers at the University of Washington exploits the relative motion between a central cylindrical nacelle and two floats. This design also uses a heave plate that behaves as both a reaction mass and a drift-reducing drogue.

Tidal Energy Converters (TECs) harvest energy from ocean currents. TECs are typically restrained by mooring systems to counter the thrust generated by running tidal turbines. Only one mooringless platform design was seen in the literature: a catamaran platform conceptualized by scientists at Toaki University, Japan, that would employ very large sails for propulsion. This sailing-type tidal platform follows a path-planning localization strategy; it is designed to minimize total hull and turbine resistance while maximizing advance speed, thereby improving sailing performance and long-term operation in areas of high wind forces.

Floating Offshore Wind Turbines (FOWTs) extract energy from prevailing wind fields and most commonly use moorings for station-keeping; mooringless FOWT designs are presently limited to theoretical or experimental studies. Recently, a semi-submersible single turbine platform was proposed that would maintain its station (waypoint-holding localization strategy) by employing azimuth thrusters mounted on the bottom of each of its three outer columns. Similarly, a very large, waypoint-holding, FOWT platform was conceptualized with two large propellers that consume part of the energy harvested onboard to control its position. An alternative platform concept that uses a planning strategy instead, is a very large floating structure encompassing 11 wind turbines and that is propelled by maneuvering 4 large sails. For a drift-reduction mooringless solution, researchers at the University of Ulsan, Korea, are currently working on the development of a toroidal-shaped, honeycomb floating structure equipped with flapping plates that could be configured to act in a predominant direction.

Unoccupied Underwater Vehicles

UUVs—specifically, remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), gliders, and profiling floats—can operate underwater. These platforms allow for sensing of the coastal and open ocean at much higher spatial and temporal resolutions, as well as at lower cost, than using techniques that rely on large crewed ships or moorings.

ROVs are controlled by human operators via tethers that link the submersibles to external control systems. Their horizontal and vertical motion can be controlled but is limited by the length of tether used. Because they are tethered by definition, ROVs are not discussed any further.

AUVs are self-contained vehicles that use an active propulsion and steering system that is controlled using onboard electronics with no, or limited, human interaction. Commercial examples include AUVs manufactured by BAE Systems, Kongsberg, and Teledyne.

Gliders and profiling floats are self-contained UUVs that use buoyancy control to provide vertical propulsion. The difference between them is that gliders have hydrodynamic fins that can propel the vehicle forward as it sinks and rises. Examples of commercially available glider platforms include those manufactured by iRobot, Teledyne, and Bluefin Robotics. Profiling floats, made by various manufacturers, are deployed worldwide as part of the international observation Argo fleet.

A typical UUV uses a battery that powers various subsystems including the propulsion, navigation, sensing, and communication systems, although there may be an opportunity to power these devices using ocean gradients, primarily thermal, for this purpose. One such example is the Slocum glider that uses ocean thermal gradients to extract energy that can be used for propulsion.

Station-Keeping Methods

The main types of station-keeping methods encountered in this report achieve their intended localization strategy by means of drift mitigation, steering, and/or propulsion.

Drift mitigation is commonly accomplished via drogues and sea anchors. Stand-along steering subsystems use control surfaces (e.g., ship rudder, wing sail, etc.) that react to ocean currents, waves, or winds to provide varying-degrees of course adjustments. Combined steering and propulsion subsystems include differential thrusters, directional thrusters separate from a primary thruster that cause the platform to pitch up/down or yaw clockwise/counterclockwise, or vectored thrusters that direct the propulsion in a range of directions relative to the platform's local coordinate system. Propulsion is often achieved by running a motor and applying active control strategies but can also involve buoyancy shifts and using sails to generate lifting forces that propel a platform in a desired direction.

Future research is primarily expected to take place in the form of a technoeconomic analysis that would aim to determine the technological viability, cost, and added value of mooringless station-keeping use cases identified through this research, including docking for UUV recharging or for georeferencing drifter buoys, deep-sea floating wind farms, U.S. Navy sonar arrays, and a Pacific Ocean wave buoy network.

Table of Contents

List of Figures

List of Tables

1 Introduction

The term “ocean platform” is used generically in the scientific community to describe systems and devices that operate in the ocean, whether on the surface or underwater, and whether they are anchored (such as moored buoys) or mobile (such as surface and underwater vehicles).

For anchored platforms, the cost associated with mooring systems is often a sizable portion of capital expenditures for platforms deployed in the open ocean. These systems are designed to withstand continual dynamic loading to avoid fatigue failure and often need to be over-designed to survive infrequent extreme events, making their construction, installation, and maintenance considerably costly (Curcio et al. 2006). For certain applications, mooring cables become impractical if, for example, the deployment site is in very deep water or if the mission duration will be relatively short. As an alternative, ocean platforms may be kept on-station without the use of mooring cables or anchoring by using an energy source to offset or control drift, though the performance of such methods and their station-keeping ability varies widely.

The challenge for mobile platforms, on the other hand, is that they have traditionally relied on combustion engines or batteries to control their movement, which, depending on the specific systems, may be expensive, cause pollution and have a short operating life. In the past decade, however, new technologies have been and continue to be developed to power ocean platforms with energy harvested from surrounding ocean resources, which may greatly expand the application of these kind of platforms.

This research is motivated by prior investigations of the Functional Requirements for ocean observing systems, in which better understanding of mooringless systems was identified as a common need among a variety of applications and end-uses for ocean systems (Cavagnaro et al. 2020). The goal of this report in particular, is to categorize and characterize the different station-keeping[1] methods used by a variety of mooringless ocean platforms as reported in the scientific literature and seen in related commercial industry. Emphasis is placed on the systems that use marine renewable energy (MRE), such as waves and currents, because MRE is a key focus of the U.S. Department of Energy’s Powering the Blue Economy (PBE) initiative. By deepening our understanding of the methods used for keeping platforms on-station or following a desired path, it is hoped that they can be applied to offshore platforms to help reduce loads on mooring cables, or eliminate the need for them altogether when appropriate, thus removing a barrier for further development of innovative marine technologies.

The body of this report is organized as follows: Section 2 analyzes moored systems to provide background for traditional station-keeping; Section 3 presents a preliminary literature review resulting in identified groupings of mooringless ocean platforms and a descriptive methodology

[1] Station-keeping is used here broadly to describe a platform’s ability to hold or control its location in the ocean, i.e., the platform may be moving.

for categorizing mooringless station-keeping methods; Section 4 presents an expanded review of scientific literature and targeted commercial technologies to inform an analysis of ocean platforms in three areas of interest (buoys, surface drifters, and unoccupied[2] surface vehicles or USVs; offshore renewable energy systems; and unoccupied[2] underwater vehicles or UUVs); Section 5 synthesizes key station-keeping methods identified in the previous sections; and Section 6 outlines suggested topics for future research.

[2] Vehicles able to operate without a human occupant. Also seen in the literature as *uncrewed* and *unmanned*.

2 Background: Moored Station-Keeping

Here, we consider the station-keeping method of moored buoys as a baseline of performance for non-moored systems.

2.1 Moorings

A mooring for a buoy at its most basic function is meant to resist the forces of wind, waves, and currents that act on the buoy. A moored buoy can use a wide variety of mooring systems to accomplish this. Choosing one mooring system design over another is dependent on a number of factors, including water depth, tide fluctuations, seafloor conditions, seafloor impact restrictions, expected current profiles and sea conditions, system lifetime, accuracy requirements for the buoy location, and sometimes requirements to provide a power or data connection to the sea floor or elements along the mooring string.

Buoys are kept in place using three general types of mooring systems: taut-line, semi-taut, or slack-line moorings. All three methods rely on mooring lines, which typically include some combination of steel cable, wire rope, nylon line, polyolefin floating line, glass float balls, and chain. At the bottom of the mooring line is a weight or anchor to keep the buoy affixed to one location. There are several differences between these methods, but one of the most basic differences is the length of line used relative to the water depth, or scope.

Taut-line and semi-taut moorings have a scope of around 1:1 and thus have a relatively small watch-circle, meaning they have limited freedom to swing in a circular arc around the anchor point. In this type of arrangement, mooring lines have what is referred to as elastic compliance. That is, the elasticity of the mooring line allows the surface buoy to move in response to waves, winds, and currents.

A slack-line mooring has a scope greater than one; in shallower water the ratio may be closer to 7:1 or more, in deeper water it might be closer to 1.4:1. There are two common types of slack-line systems: chain-catenary and inverse-catenary. In the chain-catenary system, a length of heavy chain resting on the seafloor connects the mooring line to the anchor or weight. This removes vertical load from the anchor or weight, but this system becomes impractical at great depths and the watch-circle of the chain can damage the surrounding environment.

In the inverse-catenary system, an s-curve or gentle bend is introduced into the mooring line by using a lower density material in the desired section of the mooring line, or by attaching floats to the line section. This s-shaped bend in the mooring line provides the necessary compliance for the surface buoy. This method is not well-suited to areas with large sea states and generally has more freedom to move and swing about on its tether, resulting in a relatively large watch-circle. The descriptions of these mooring systems have been simplified; in practice mooring systems have many different design elements. See Figure 1 for an example of a slack-line mooring system for a National Oceanic and Atmospheric Administration (NOAA) buoy and Figure 2 for an example of a semi-taut mooring system.

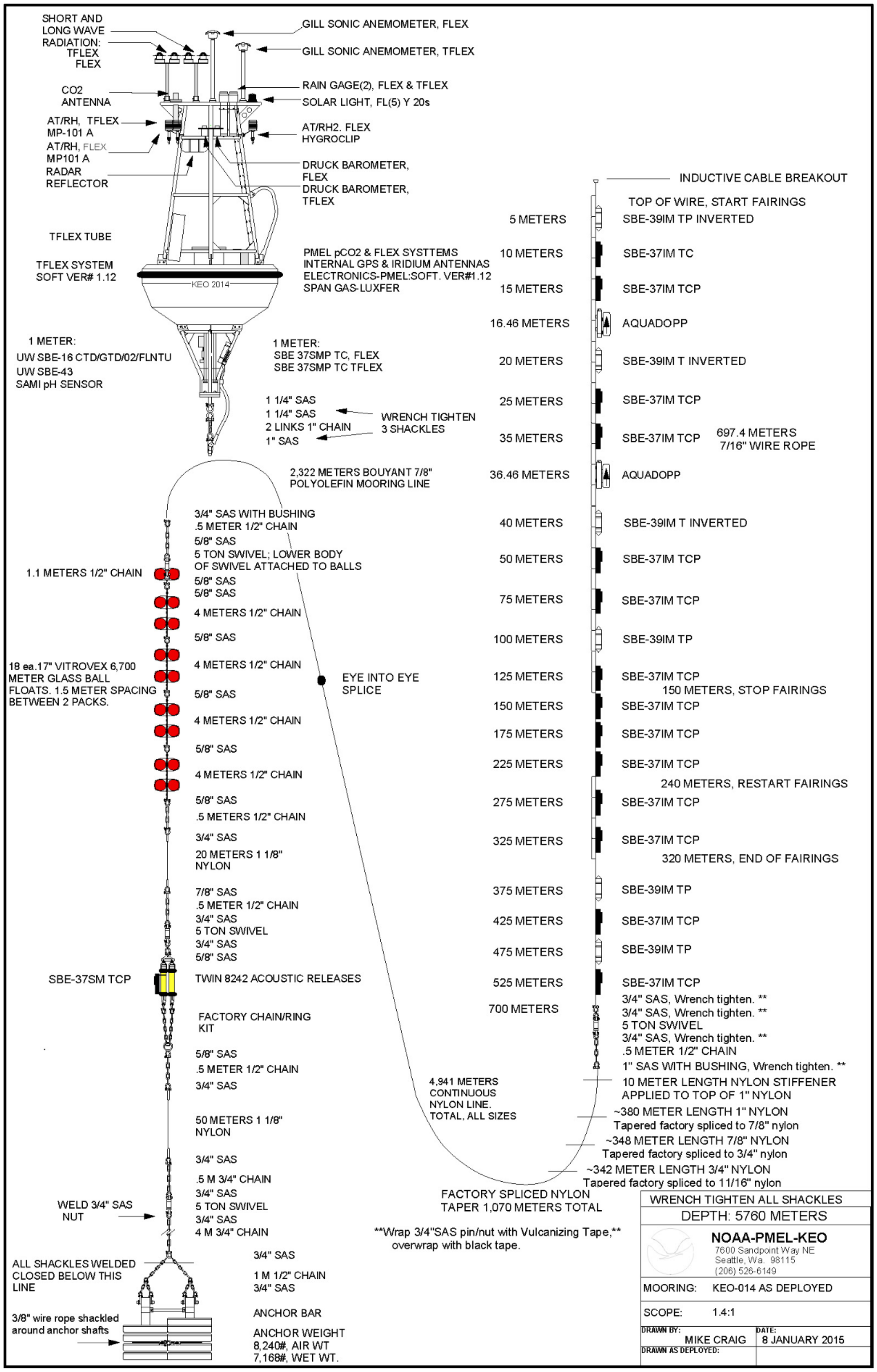

Figure 1. Example of a slack-line mooring system from the NOAA Pacific Marine Environmental Laboratory.

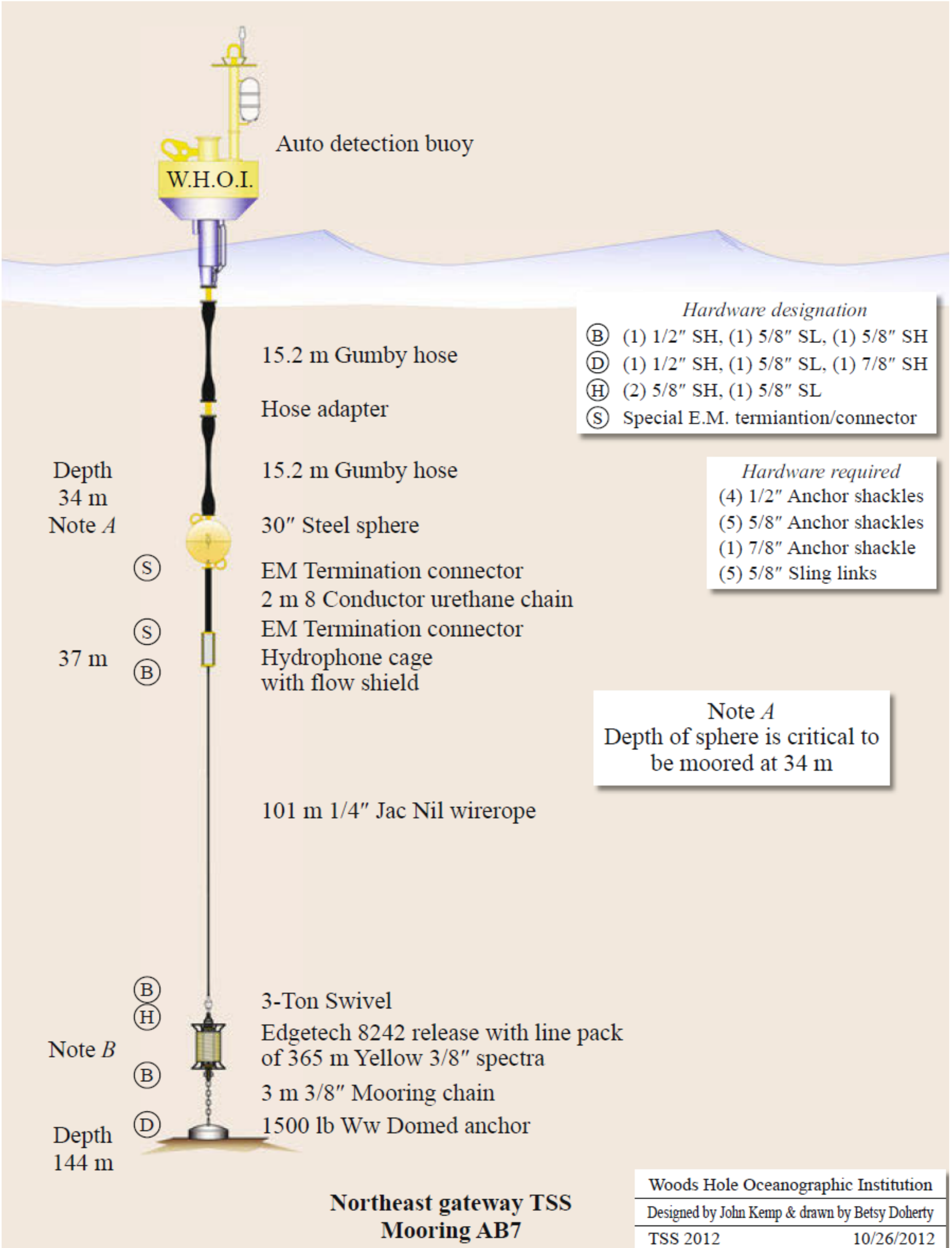

Figure 2. Example of a semi-taut mooring system.

Figure courtesy of Woods Hole Oceanographic Institution(Dhanak and Xiros 2016)

2.2 Mooring Limitations

While traditional mooring lines are currently a useful and necessary part of keeping ocean platforms on-station, they have various limitations. Opportunities for improvement include mechanical failures over the lifetime of a mooring system, the cost associated with deploying and maintaining systems, and minor environmental impacts caused by fixed moorings.

Global attention to mooring line failures that have cost the oil and gas industry billions of dollars over the past decade has created an interest in characterizing the reliability of existing buoy mooring designs. Offshore buoys provide benefits such as atmospheric and oceanic data collection and tsunami detection, and stable mooring lines are essential to the success of these systems. To identify areas for improvement, an analysis done by the National Institute of Ocean Technology compiled failure in time (FIT) values for various buoy components and ascertained that the highest failure rates appeared in buoyancy floats, followed by dead weight chains, and anchor chains. Mechanical failures also occurred in connectors and ropes to a lesser extent. Individual case studies reveal failures caused by abrasion, mistakes made during deployment procedures, and corrosion (Venkatesan et al. 2015). Additional reasons buoys can fail include vandalism, fatigue, and fish bites. Some of these failure modes can be mitigated through design changes, such as armored lines to protect against fish bites or making buoys more difficult to board.

Besides the cost associated with component failure, necessary replacements, and maintenance trips, traditional mooring systems can be expensive. The cost of mooring lines and deployment varies depending on the size of the device deployed, depth and energy of the water in which it is deployed, and the target location for deployment. These factors affect considerations such as anchor requirements, mooring design, and expected line fatigue. Taut-line mooring designs may see considerable expenses caused by specialized anchors, while conventional catenary moorings are more affordable (Sound & Sea Technology Engineering Solutions 2009).

Mooring deployments in certain cases also increase the cost and complexity of fixed mooring designs. Generally, buoy moorings can be deployed from many kinds of boats including tugs, supply vessels, and general-purpose support vessels. However, large anchors for deep water (up to 2,000 feet) necessitate specialized anchor-handling tugs to deploy them, which are more difficult to locate (Sound & Sea Technology Engineering Solutions 2009). Any deployments in arctic waters further complicate the process because air support is generally necessary. Moorings are typically installed by spooling out the mooring line first and deploying the anchor last, although deployments in ice-covered waters lead with the anchor and require stronger lines to deal with increased line tension during deployment (Kemp et al. 2005).

Environmental impacts must also be considered when evaluating traditional mooring lines. Buoy mooring lines have no loose ends so marine wildlife entanglement is unlikely (Harnois et al. 2015). Entrapment, which is the disorientation of marine animals caused by many mooring lines and cables, is also unlikely because buoys are not generally found in clusters. However, heavy mooring lines still have the potential to cause localized impacts on the seabed, particularly in the chain-catenary design. When the mooring chain is dragged across the sea floor in response to wind and waves it wears away vegetation surrounding the mooring anchor. These pockets of barren sea floor are called mooring scars, and they can persist for decades after the mooring is removed; in extreme cases, the mooring scars can act as a locus for continued erosion (Serrano et al. 2016). The intensity of this effect on the environment varies depending on the mooring design. Improved designs, such as the three-chain cyclone mooring, have been created to minimize environmental damage.

While traditional mooring lines may be a necessity now, a shift away from conventional mooring techniques has the potential to reduce the cost of deployment and maintenance, component fatigue, and environmental impacts.

3 Methods

The content of this report is based on a thorough literature review of ocean platform station-keeping without the use of moorings. A preliminary survey of the literature yielded 72 scientific articles and technical reports that cover a wide range of station-keeping methods and applications (Appendix A). A categorization framework was then established to identify common themes from the compiled library to inform potential research gaps. This framework collected data that categorized the research presented in each of the articles based on its year of publication (Figure 3), the type of investigation conducted (Figure 4.a), the platform of interest (Figure 4.b), the platform's location in the water column (Figure 5), and more.

Figure 3 shows that research on mooringless station-keeping methods appears to have increased dramatically within the last decade. It is also important to highlight that most of the platforms encountered in this review were large ships using dynamic position with azimuthing thrusters (such as for oil and gas exploration), and a large portion of the research was focused on modeling and simulation experiments involving novel control algorithms. This preliminary analysis also led the research team to more appropriately segment the various platforms into three broad categories: buoys, surface drifters, and USVs (see Section 4.1); offshore renewable energy systems (see Section 4.2); and UUVs (see Section 4.3). Ships and platforms were not generally included in this review because they tended to use large diesel engines and were less likely to be energy constrained.

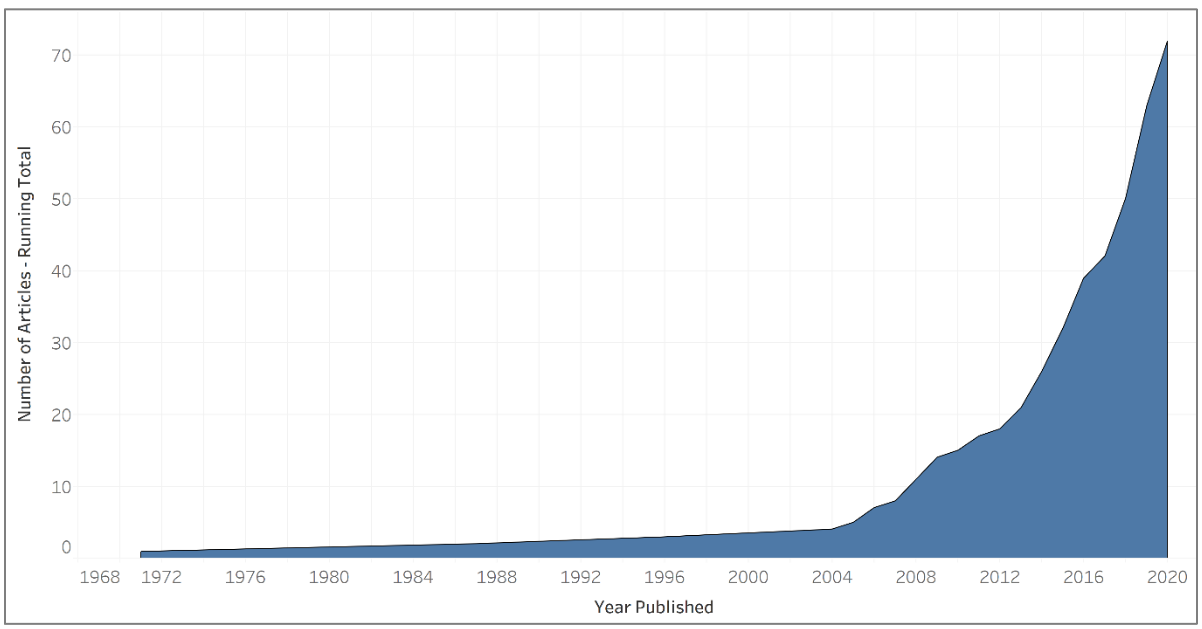

Figure 3. Year of publication of literature focused on mooringless station-keeping methods.

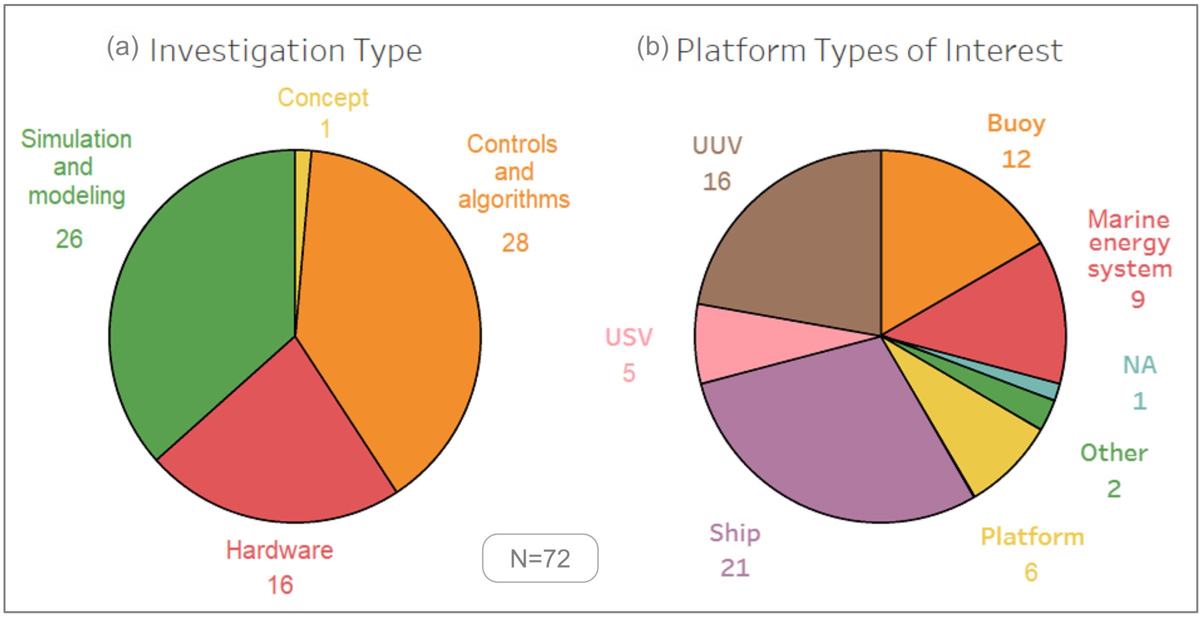

Figure 4. Breakdown of (a) investigation approaches and (b) platform types identified in the preliminary literature review.

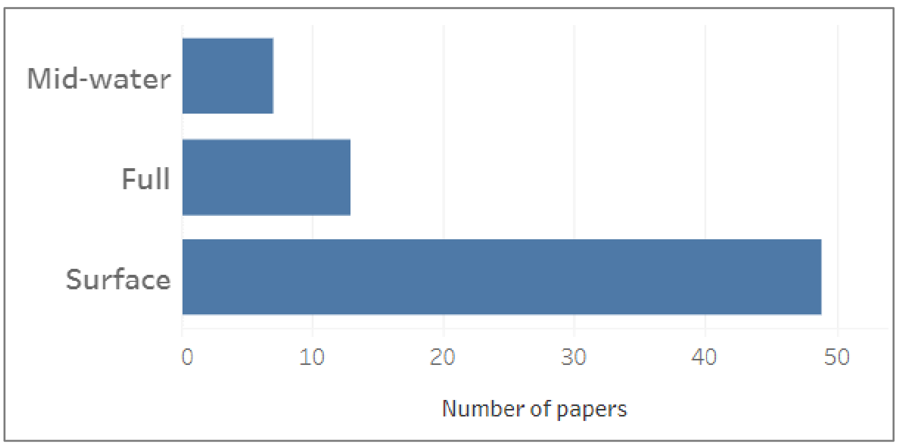

Figure 5. Platform location in the water column as noted in each paper in the preliminary literature review.

Currently, there are no standardized methods of categorizing mooringless station-keeping technologies. Initially, a simplistic approach was explored that categorized platforms based on their energy usage as either “active” or “passive.” An active system was considered to be one that relied on an internal source of energy (e.g., battery or an internal combustion engine) to provide the energy for propulsion to control the ocean platform’s position. A passive system positioned itself by redirecting or harvesting renewable energy resources, such as waves or wind (e.g., flapping fins actuated by wave energy). Figure 6 summarizes the energy source and usage of the various platforms encountered in the literature.

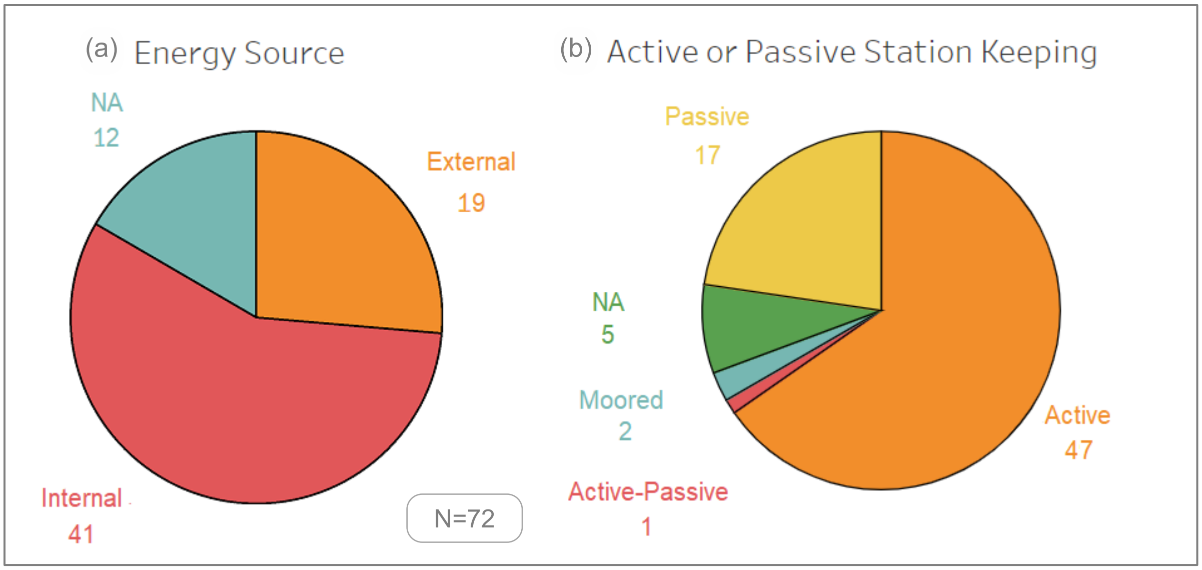

Figure 6. Breakdown of station-keeping (a) energy source and (b) energy usage discussed in the preliminary literature review.

After this preliminary literature review and subsequent discussions, it became apparent that this simplistic categorization was too subjective and left much to interpretation. For example, if a drifting float controlled its motion using actuating fins that were acted on by ocean currents, but the fins were articulated using battery power, would this be considered an active or a passive system? There was also confusion as to whether the categorization applied to the station-keeping method itself, or the ocean platform as a complete system. As an alternative, a more appropriately descriptive framework was developed to categorize mooringless station-keeping methods based on their predominant energy source and consumption, and their localization strategy; this terminology is described in detail in Sections 3.1 and 3.2 and is used throughout the rest of the report.

3.1 Predominant Energy Source and Consumption

Predominant energy source and consumption refers to the main component of power production/harvesting and usage on the platform. The power produced and consumed on a platform may go to a variety of loads, including propulsion, communications, or payloads (instruments and sensors). For each platform it was difficult to isolate the portion of energy that was used for station-keeping, so assessment of the predominant energy source refers to the system as a whole and not necessarily the portion of the system responsible for the localization strategy. Here, we consider three types of energy sources: renewable, nonrenewable and hybrid.

3.1.1 Renewable

Depending on their geographic location, ocean platforms often have multiple forms of renewable energy available to them, including solar, wind, wave, currents, as well as ocean thermal and ocean salinity gradients. Renewable energy is most often harvested and converted into electrical energy and then stored in a battery and used to power electrical equipment such as ocean instruments or thruster motors when needed. For example, a typical NOAA coastal weather buoy uses four 30 W solar photovoltaics (PV) panels to feed a 1.34 kWh lithium-ion battery pack that powers the buoy instrumentation (Copping et al. 2020). Some platforms, however, use renewable energy sources directly for propulsion. The use of MRE is of particular interest to PBE initiatives.

3.1.2 Nonrenewable

Nonrenewable systems typically refer to internal battery systems or internal combustion engines that are not replenished at sea using renewable resources. Diesel engines are more common on platforms that need large amounts of on-demand power, such as larger unoccupied surface vehicles.

Industry examples of fossil-fuel powered platforms are common: oil and gas deep water drill ships that use dynamic positioning; and USVs such as the Kongsberg Sounder USV, the ASV C-Stat Station-Keeping Buoy, or the C-Worker 4 ASV. Numerous systems also rely entirely on batteries and have no ability to recharge autonomously at sea using harvested energy from the natural environment.

3.1.3 Hybrid

Hybrid systems are those that use equal, or nearly equal, amounts of renewable and nonrenewable energy inputs to operate, such as a diesel engine and solar PV.

3.2 Localization Strategy

Mooringless platforms vary in their capability to hold their position in the ocean, referred to here as their localization strategy. Keeping an ocean platform at a specified location or along a predetermined path is a kinetic energy challenge. We have identified three generic localization strategies that are employed by platforms seeking to address this challenge: drift reduction, path-planning, and waypoint-holding. Drift reduction is the most basic method and the least energy intensive, while waypoint-holding is the most complex and energy intensive.

3.2.1 Drift Reduction

With this strategy, a platform can move relatively freely but a system is in place to reduce its drift and thus avoid abrupt changes in station.

3.2.2 Path-Planning

Path-planning refers to a platform’s ability to follow an intended course and is more applicable to platforms capable of self-propulsion. In this localization strategy, the platform is tasked with using its onboard navigation and propulsion systems to follow a specified series of waypoints or course heading. More energy-intensive methods involve the use of electric thrusters or internal combustion engines, which, in combination with navigation systems and feedback controllers, can lead to more accurate path-following at specified waypoints.

3.2.3 Waypoint-Holding

Waypoint-holding is the ability of a platform to hold position at a single waypoint or reference location instead of following an intended path. An imaginary boundary is often specified around the waypoint, referred to as the watch-circle. The platform uses its onboard navigation and propulsion system to keep it within the watch-circle, or within a certain pre-determined area. A platform in a waypoint-holding mode is sometimes referred to as a “virtual mooring.” There are numerous ways a platform may accomplish this, such as moving in a figure-eight, circle, or square around the waypoint; or repeatedly drifting over the waypoint by maneuvering up-current or up-wind before each drift. Waypoint-holding is a more computational and energy demanding task for most platforms, especially for smaller watch-circles.

4 Platform Analysis

This section describes various ocean platforms and the methods they use to station-keep based on the internally derived terminology described in Section 3. Special attention is paid to mooringless systems, but at times moored systems are also discussed to provide a reference of current technologies. Platforms are segregated into three areas of interest: buoys, surface drifters, and USVs (Section 4.1); offshore renewable energy systems (Section 4.2); and UUVs (Section 4.3). Additional commercial devices were identified beyond the preliminary literature review through targeted web searches and are included in the following analysis.

4.1 Buoys, Surface Drifters, and Unoccupied Surface Vehicles

4.1.1 Platform Description

This analysis is limited to considering the different methods of station-keeping for buoys, surface drifters, and USVs, all of which are relegated to the water's surface. These platforms are as varied in size and shape as the missions they perform.

Buoys and Surface Drifters

The terms buoy, float, and drifter are often used interchangeably and there is no widely agreed-upon naming convention. The term float is often used to describe both surface platforms and subsurface or profiling floats. Because profiling floats dive underwater, they are discussed in the UUV section of this report (Section 4.3).

Buoys are buoyant objects that sit on the water's surface. This term is generally used to refer to anchored floats that indicate or monitor (when equipped with appropriate instruments and hardware) locations of interest. This could include marking shipping lanes or mooring sites, or monitoring locations of scientific interest such as reefs. Examples include NOAA's National Data Buoy Center (NDBC) buoys and navigational buoys (see Figure 7). Buoys are sometimes referred to as Eulerian platforms to indicate that they remain at a single location and that their sensors sample the air or water as the fluid moves past them.

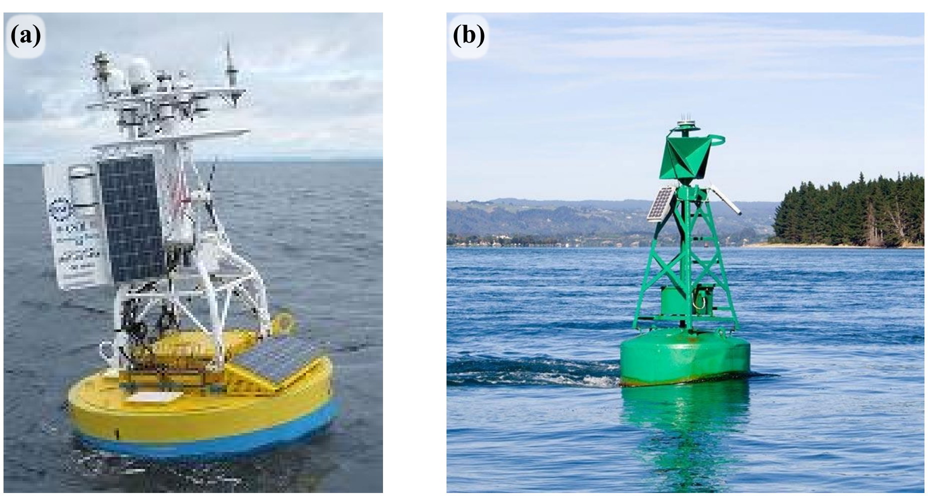

Figure 7. (a) NDBC OOI Station 46098, located off the western coast of Oregon, and (b) example navigational buoy, manufactured by JFC Marine.

If a float does not remain at single station and cannot control its vertical position it is simply called a surface drifter. Modern drifters are sometimes referred to as Lagrangian drifters because the location of the measurements they make moves with the flow. The Global Drifter Program includes ~1,300 drifters in a variety of standard types (Figure 8) ("Drifter Types | Lagrangian Drifter Lab" n.d.).

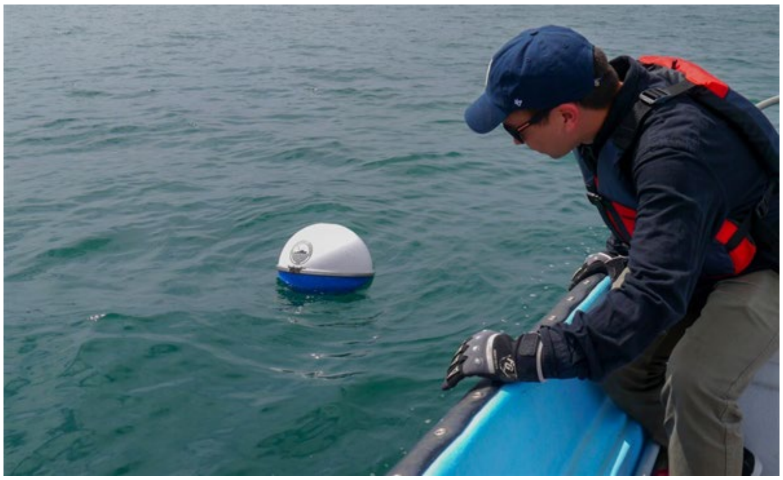

Figure 8. Scripps SPV drifter, part of the Global Drifter Program.

Unoccupied Surface Vehicles

USVs are self-propelled mobile platforms limited to surface operations for conducting a variety of ocean science, security, and military, and industrial applications. Many USVs can leverage navigation control algorithms, global positioning systems (GPSs), and their propulsion to station-keep at a designated waypoint. This ability to propel themselves and station-keep on command provides the benefits of both mobile and stationary platforms. Examples of USVs are provided in Section 4.1.5 where they are presented in relation to their predominant energy source (Figure 18 through Figure 22).

4.1.2 Physical Characteristics

Buoys, drifters, and USVs come in a variety of shapes, sizes, and weights. A summary of different systems from our review of 60 unmoored, autonomous surface devices is shown below in Figure 9.

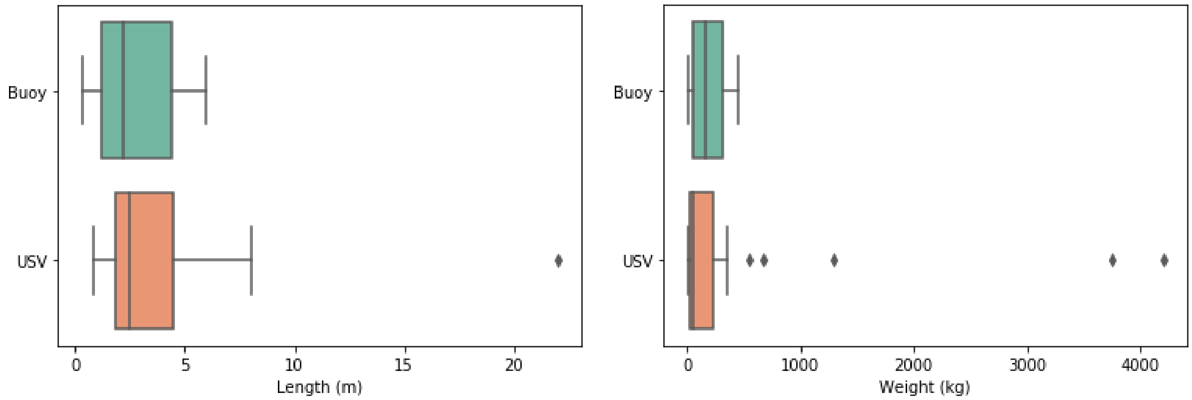

Figure 9. Length (left) and (b) weight (right) distributions of buoys and USVs.

Buoys are typically slightly smaller than USVs and have a much narrower range of lengths and weights. Generally, the buoy size is determined by the required size of the payload (instrumentation and sensors), the power source, the energy storage through batteries, the communication equipment, and any stability requirements (Dhanak and Xiros 2016). Almost all buoys are axisymmetric and generally align to one of two common shapes:

- discus and toroidal buoys have shallow drafts and large water-plane areas and are generally wave followers. Higher aspect ratio buoys have a pronounced heave resonance.
- spar buoys have large drafts and small water-plane areas and can be designed for large heave response.

4.1.3 Application of Platforms

Moored Buoys

Buoys are used for a variety of end-uses in marine science, maritime navigation, meteorology, fishing, offshore energy, or military and defense applications (Encyclopedia Britannica 2015) (Table 1). They are best suited for marking locations or monitoring small areas (low spatial resolution) over long temporal scales. The mooring keeps buoys in a relatively fixed location, but they still might wander over a given area depending on the length of the mooring relative to the water depth.

Table 1. Range of uses and attributes of moored buoys.

Buoy Application	Buoy End-use	Typical Deployment Time	Purpose
Meteorology and Oceanography (METOC)	Ocean Data Buoys	Years	Collect ocean data (wind, wave, currents, temp, etc.)
	HF Radar	Months to Years	Monitor offshore surface currents
	Floating LiDAR	Months	Monitor offshore wind sites for resource assessment
Maritime Navigation	Navigation Channel Marking	Years	Indicate areas of safe passage for vessel traffic
	Hazards	Years	Indicate areas of danger to vessels (shoals, reefs, etc.)
Military and Defense	SLOT Buoy	Years	Communications relay for submarine
Fisheries	Crab and Lobster Pots	Weeks to Months	Indicate location of fishing traps
	Fishing longlines	Days to Weeks	Indicate location of fishing lines
Communications	Wi-Fi Repeater	Years	Extend coverage area for Wi-Fi

Meteorology and Oceanography (METOC)

Above the water line, moored buoys may be equipped with meteorological sensors, communications systems (such as satellite or radio transmitters and receivers), and solar panels. Below-water, buoys may also hold various instruments, including current meters, temperature and pressure sensors, sediment traps, chemical sensors, power supplies, data recorders, and acoustic modems. Examples of buoys used for this application include the hundreds of buoys operated by NOAA's NDBC, such as the one shown in Figure 10. These buoys measure a variety of scientific parameters, mainly wind speed and direction; wave height, period, and direction; humidity; and temperature. These buoys are often deployed for years at a time and are typically serviced every year or two depending on their location (Conlee, Moersdorf, and Henderson 2005; University of Rhode Island 2020).

Figure 10. NDBC Buoy Station 44040, located in Western Long Island Sound, Connecticut.

Credit: NOAA's NDBC

Maritime Navigation

Moored buoys are used to mark the bounds of established shipping lanes. These aids-to-navigation help mariners avoid collisions and groundings by providing valuable reference points. Buoys can also be used to mark navigation hazards such as sandbars, shoals, wrecks, reefs, or even munitions testing areas for militaries. They provide an above-water indication of the danger's presence for mariners to clearly see. Buoys are also used to indicate established mooring locations for ships both large and small. In this arrangement, a large weight or anchor is left in place on the seafloor and a mooring line is connected from the weight to the surface buoy. Ships can then connect to the mooring without dropping their own anchor. Buoys used for maritime navigation applications are often deployed for years at a time and are serviced once or twice a year, depending on their location and the need (United States Government Accountability Office 2020).

Military and defense

These systems are used to monitor sites of interest to military and defense organizations—often to detect and prevent illegal activity or threats to national security. A SLOT (Submarine-Launched One-Way Transmitter or Submarine-Launched One-Way Tactical) buoy, for example, is equipped with an on-board radio transmitter for sending a message from a submerged submarine to the overwater world (Figure 11).

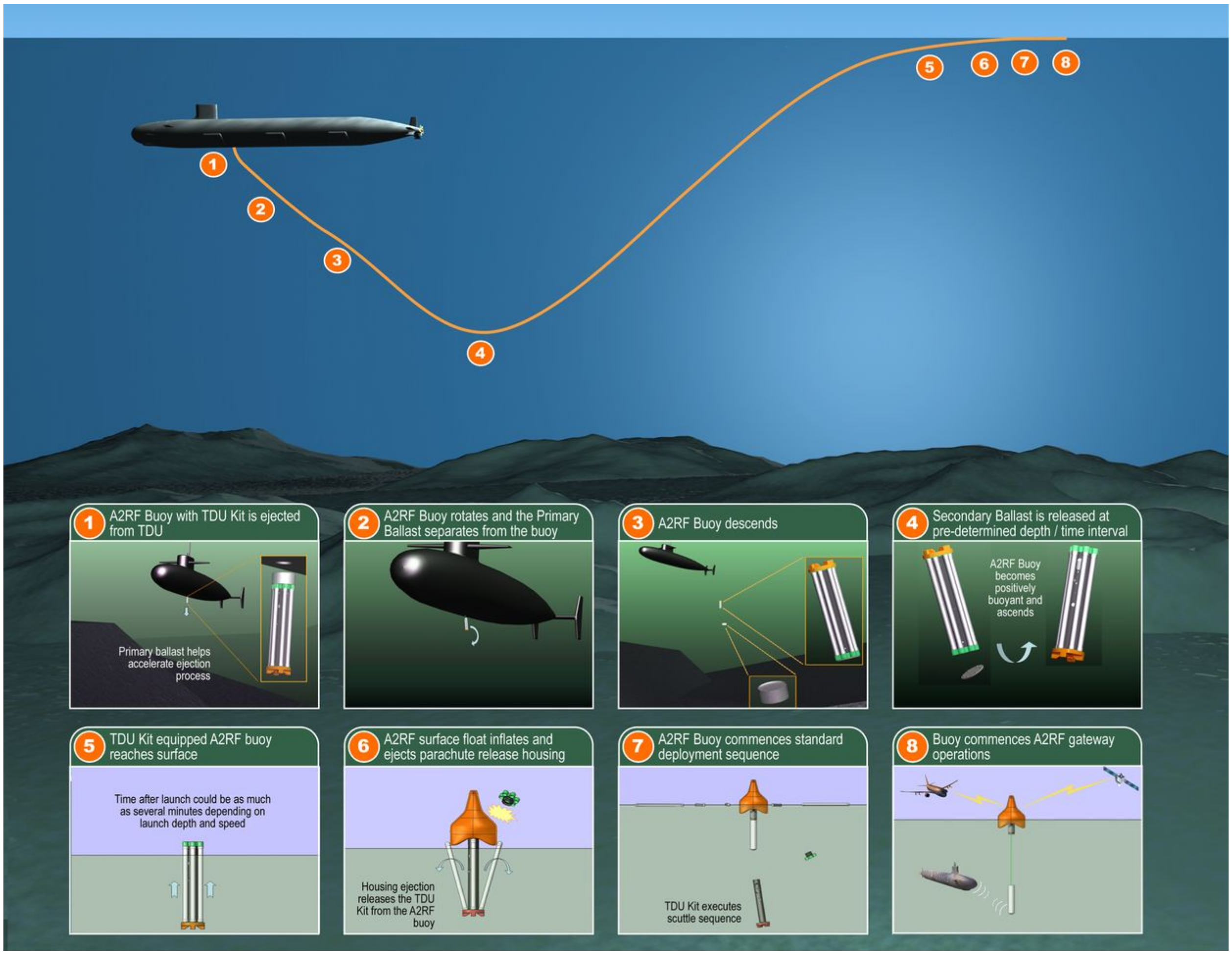

Figure 11. Overview of a SLOT buoy.

Credit: Edwards and Phys.org 2010

Fisheries

In the fishing industry, buoys (sometimes referred to as floats if they are not moored to the bottom) are commonly used to support fishing nets, mark the location of crab or lobster traps, or indicate longlines. These buoys are deployed for days to weeks at a time, depending on the species of interest, e.g., FAO Fisheries Division (2021). Another type of buoy is the Fish Aggregating Device (FAD) (Figure 12) (NOAA Fisheries 2017). FADs are makeshift buoys with organic matter or other material attached to them that will attract small fish, which, in turn, attract larger fish that are of interest to commercial fishers. FADs are revisited periodically by the fishers to find target species and are generally deployed seasonally (Holland, Jaffe, and Cortez 2000; FAO 2012).

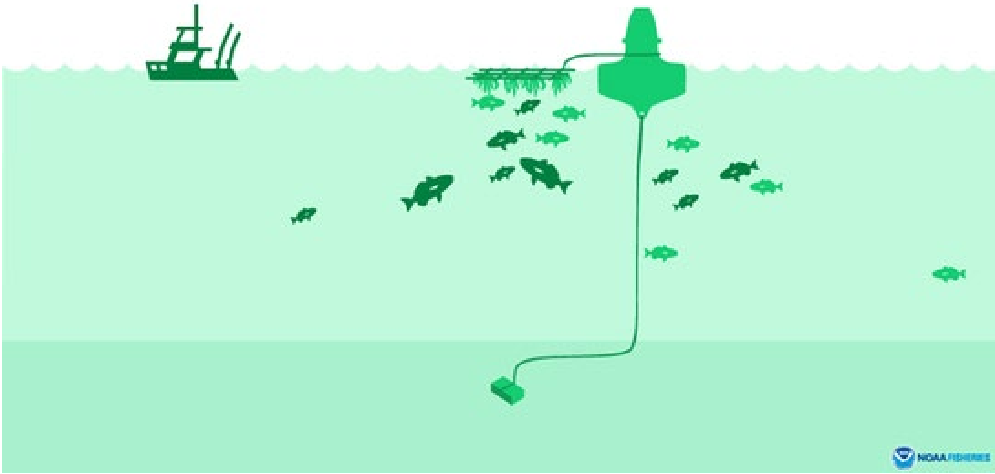

Figure 12. Fish aggregating device.

Credit: NOAA Fisheries

Communications

Buoys, in their most basic function, are used to convey and communicate information, whether at a local or global level. In our digital age, buoys are expected to convey information over great distances in near real time. This requires communication systems that enable exchange of information between satellites, underwater vehicles, or other buoys and surface systems. While nearly every buoy has some sort of a digital communication system on board, not every buoy is dedicated solely to enabling offshore communication systems. An example of using buoys to enable offshore communication systems is supplying them with cellular/Wi-Fi repeaters to increase coverage and range.

Surface Drifters

Surface drifters are typically used for ocean science applications. Relative to moored buoys, surface drifters are best suited for sampling the ocean over larger spatial scales and nearly as long temporal scales. While their drifting nature allows sampling of a larger area, they lack the ability to navigate or maneuver to exact locations. Drifters are used for applications such as measuring ocean currents, detecting harmful algae blooms or ocean chlorophyll, or measuring the extent of oil slicks.

Unoccupied Surface Vehicles

USVs can be used for many of the same applications as buoys and drifters, but because they are equipped with a means of self-propulsion they can be navigated to specific locations. USVs are best suited for monitoring large spatial scales for long temporal scales. With appropriate station-keeping methods, a USV can hold a specific waypoint acting as a buoy with a "virtual mooring." If the USV loses its ability to navigate, it is rendered a drifter. USVs are also well suited for shallow or dangerous navigation locations that traditional vessels cannot access.

Some common applications of USVs include the following:

- Marine science and meteorology
  - Monitoring tropical storm conditions.
  - Ocean mapping via high-resolution sonar bathymetry.
  - Geotechnical surveying in shallow or dangerous waters.
  - Collecting metocean data (e.g., waves, currents, temperature, salinity, humidity, pressure, radiation, dissolved oxygen, chlorophyll-a).
  - Tsunami and seismic monitoring.
- Marine biology
  - Tracking and identifying fish species.
  - Monitoring marine mammals.
- Industrial
  - Monitoring of hydrocarbon for oil and gas leaks.
  - Surveying currents near drilling rigs.
- Military and defense
  - Patrolling marine protected areas.
  - Safeguarding seaports from threats.
  - Tracking combatant submarines.
- Communications
  - Communications gateway between subsurface instruments/assets and ship or satellite communications.
  - Above-water imaging (e.g., Google Trekker mounted to top of WAM-V).

4.1.4 Operating Environments

The surface systems discussed in this section are used in all sorts of operating environments, from shallow water tropical reefs along the coast, to mid-ocean at high-latitudes, and all points in-between. As shown in Figure 13, oceanographic data buoys are used throughout the oceans, with high concentrations of systems being near the coasts simply because of their cost and ease of maintenance. Buoys deployed farther offshore are more difficult and expensive to install and maintain. Figure 14 includes other ocean-observing assets beyond moored buoys. Note that while these maps may seem cluttered, the scale is on the thousands of miles, so the spatial coverage is actually quite sparse.

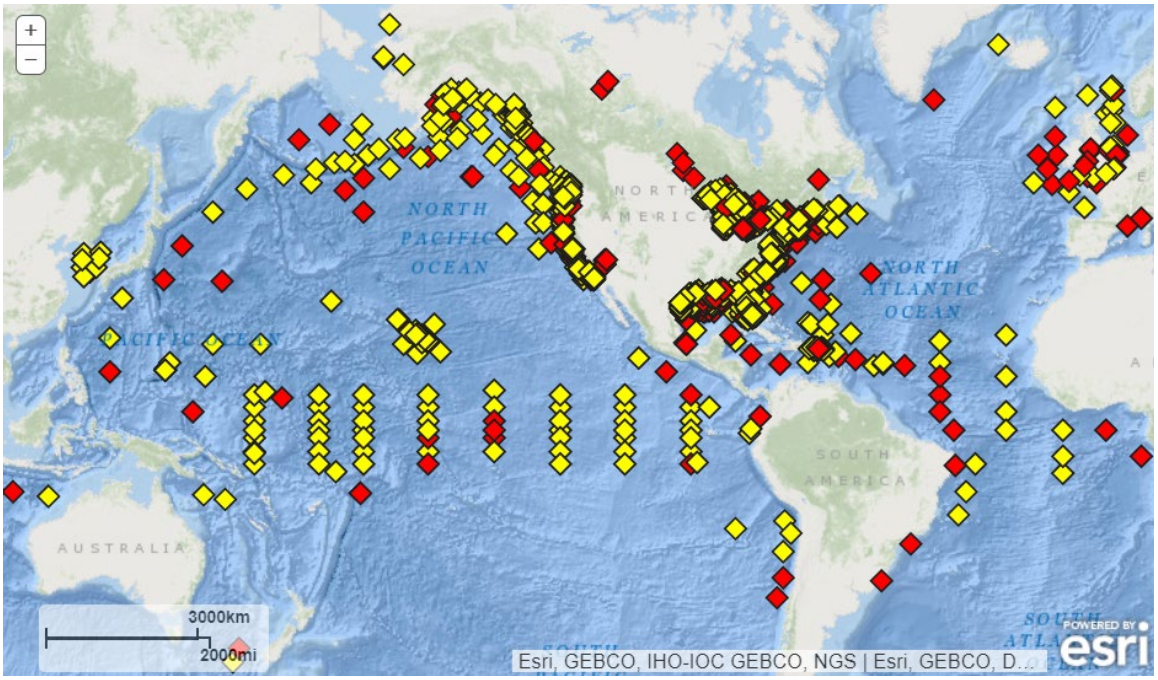

Figure 13. Global map of moored buoys.

Credit: NOAA's NDBC

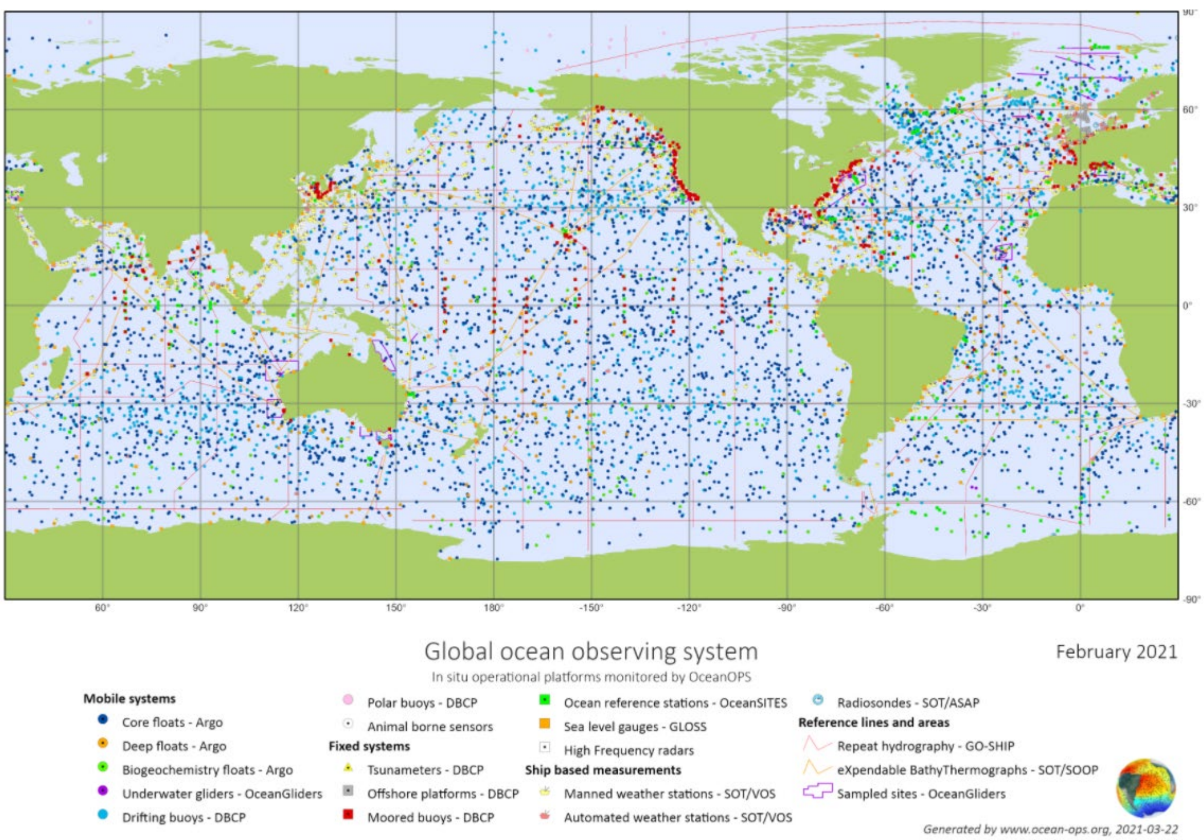

Figure 14. Global ocean-observing assets including drifters, floats, moored buoys, and gliders.

Source: OceanOPS 2021

The surface platforms discussed here are mostly concerned with surface winds and currents because they are the predominant disturbing forces that must be resisted or acted against to station-keep at a particular location. Figure 15 provides an overview of mean current speeds at or near the surface. While large swaths of the ocean have surface currents below 10 cm/s, there are some areas, particularly in western boundaries of ocean basins, where the currents can exceed 1 m/s, like the Gulf Stream in the North Atlantic or the Kuroshio Current in the North Pacific. Surface wind speeds can also vary greatly across the globe (Figure 16).

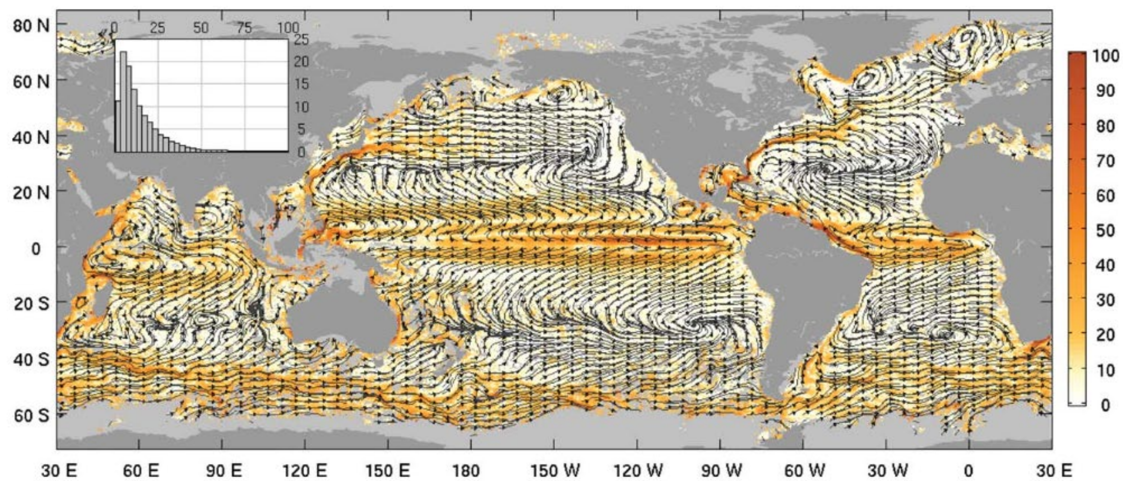

Figure 15. Mean current speeds (colors, in cm/s) from near-surface drifter data with streamlines (black lines).

Adapted from Lumpkin and Johnson 2013.

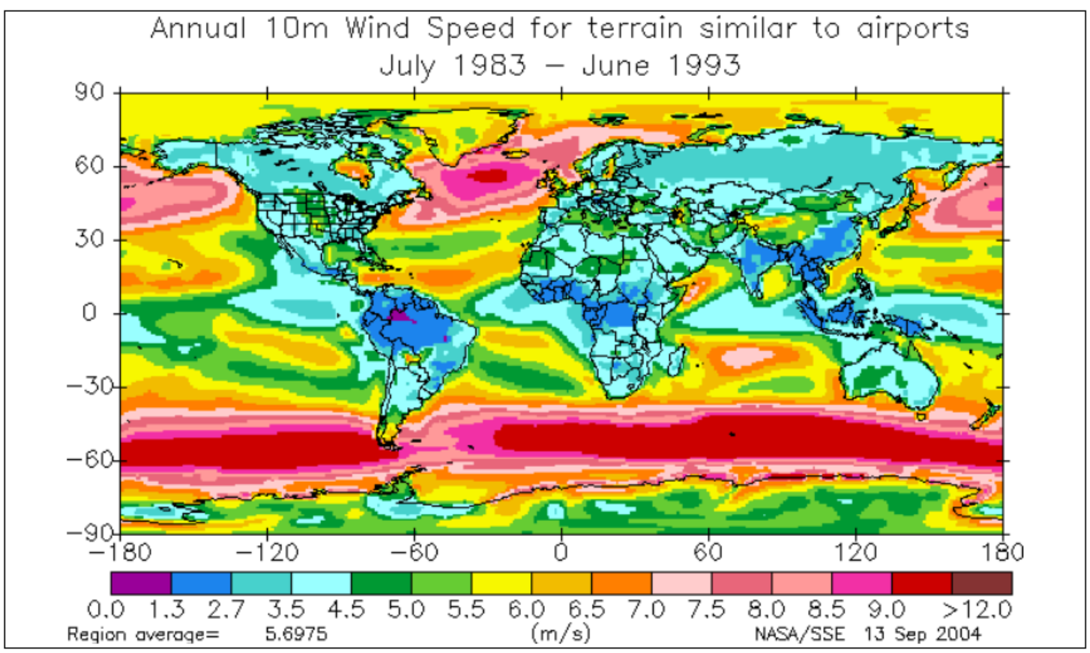

Figure 16. Average annual surface wind speeds are shown to vary significantly, from 2.5 m/s near the mid-latitudes to 12 m/s at higher latitudes.

4.1.5 Predominant Energy Sources and Consumption

As noted in a PBE report outlining opportunities for using MRE in maritime markets (Livecchi et al. 2019), navigation aids and ocean-observation installations are commonly powered by diesel generators, solar panels, or batteries. At present, wave energy is used in only a small number of applications.

Unmoored, Station-keeping Buoys

Figure 17 shows mooringless buoys that use renewable, nonrenewable, or hybrid energy for propulsion and for monitoring sensor power needs. The Wave Turbine System (WTS), under development by Pohang University of Science and Technology, is an example of a mooringless system that has a renewable power source. It is conceptualized as a three-part system with a floating body at the surface, a submerged wave-induced turbine, and a propulsion unit, which may be a Wave Glider (see following subsection), at the bottom (Figure 17.a; Joe et al. 2017). In contrast, the C-Stat station-keeping buoy uses only nonrenewable energy via a combined diesel-electric power system (Figure 17.b; L3Harris 2014). Finally, an example of hybrid energy generation and consumption is seen in the Gatekeeper buoy currently under development by the U.S. Navy (Figure 17.c; DaSilva et al. 2009). In concept, the Gatekeeper will allow for alternative energy sources including solar energy, fuel cells, and kinetic energy.

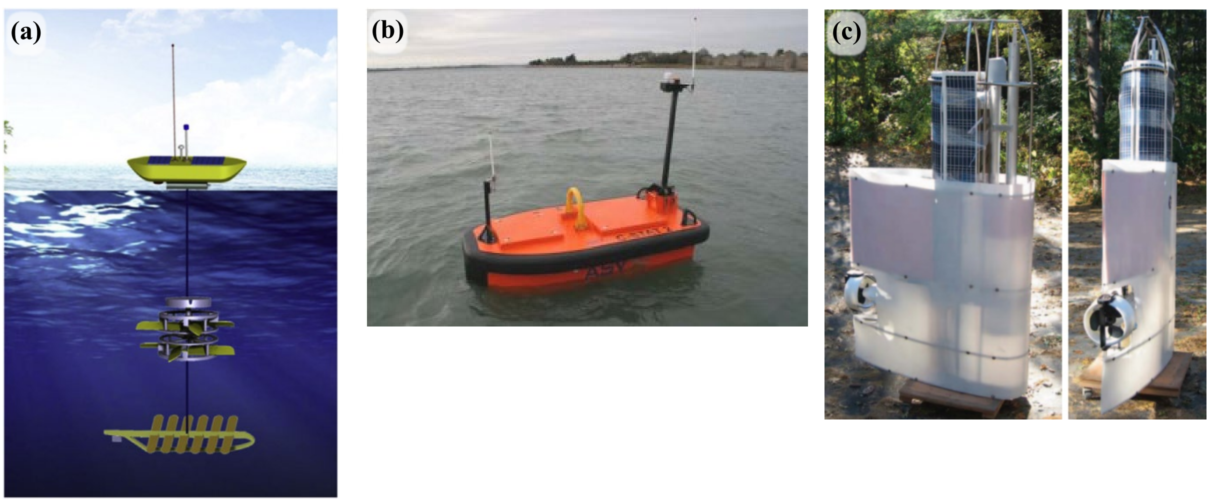

Figure 17. Station-keeping buoys and their predominant energy source: (a) wave turbine system, renewable (b) C-Stat, nonrenewable, and (c) Gatekeeper, hybrid.

Photo and figure credits: (a) Joe et al. 2017, (b) L3Harris 2014, and (c) DaSilva et al. 2009

While moored buoys can be deployed for years at a time, the length of mooringless buoy deployments is limited by the additional power needed to maintain station. At present, with the prevalence of nonrenewable energy sources, this typically results in short deployment capabilities. The advancement of renewable technologies in this area could lead to longer deployments (on the order of years), but most of these are still under development. Examples of buoys for each of the predominant energy sources are listed in Table 2.

Table 2. Energy sources and deployment duration of unmoored autonomous buoys.

Name of device	Energy source	Deployment duration
ABA (Nishida et al. 2016)	Nonrenewable battery	24 hours
ASV C-Stat (L3Harris 2014)	Nonrenewable, hybrid diesel and battery power system	4 days
Bunch of Buoys (Zoss et al. 2018)	Nonrenewable battery	2 hours, but could be extended with additional batteries
ENDECO Type 1120 (Hanlon 1987)	Hybrid, wind for propulsion, solar for instrument power with marine batteries for storage, diesel engine, and 100 gal fuel tank	Not reported
Gatekeeper (DaSilva et al. 2009)	Hybrid, propulsion by electric thruster with Li-ion battery that stores energy generated by the Salt Water Activated Power Systems (SWAPS), which uses a metal alloy to react with seawater to produce hydrogen. Also generates secondary power with solar panels.	Not reported, planned for long life deployments
Automar (Waveco AS 2020)	Renewable, subsurface wave energy harvesters	Expected to be on the order of years, but still under development
Sealandaire POS-SKB ("POS-SKB – SeaLandAire Technologies Inc." n.d.)	Renewable wind, wave and solar harvesting	Over 120 hours
WTS (Joe et al. 2017; 2014)	Renewable, modified wave glider propulsion unit	Not reported, planned for long-term, self-sustained deployments

Unoccupied Surface Vehicles

As shown in Figure 18, some commercially available USVs are fully or predominantly powered by renewable energy (solar, wind, waves). Examples include the Wave Glider, which uses wave power for propulsion and battery/solar panels to power the onboard sensors and communications instruments (Bingham et al. 2012); the Autonaut, which uses wave power for propulsion (an auxiliary electric thruster is available) and battery/solar panels to power the onboard sensors and communications instruments; and the Saildrone, which is wind- and solar-powered and is used for a variety of oceanographic missions. There are two different sub-models of Saildrones, the 7m Explorer and the 22m Surveyor.

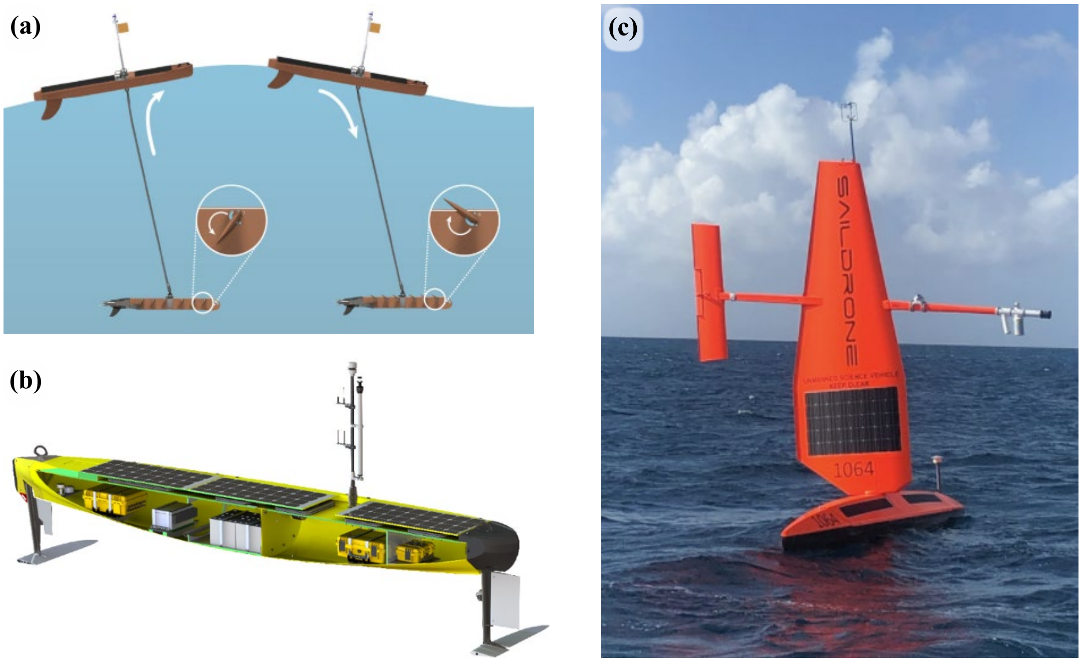

Figure 18. USVs with renewable energy sources: (a) Wave Glider, (b) AutoNaut, and (c) Saildrone.

Photo and Figure credits: (a) Liquid Robotics 2020, (b) Autonaut Ltd. 2019 , and (c) Saildrone 2021

Other USVs on the market are battery- or diesel-powered like the USVs from Marine Advanced Robotics, Inc. (Figure 19), Kongsberg (Figure 20), and L3Harris (Figure 21). The specific energy source for each system is noted in the caption of each figure.

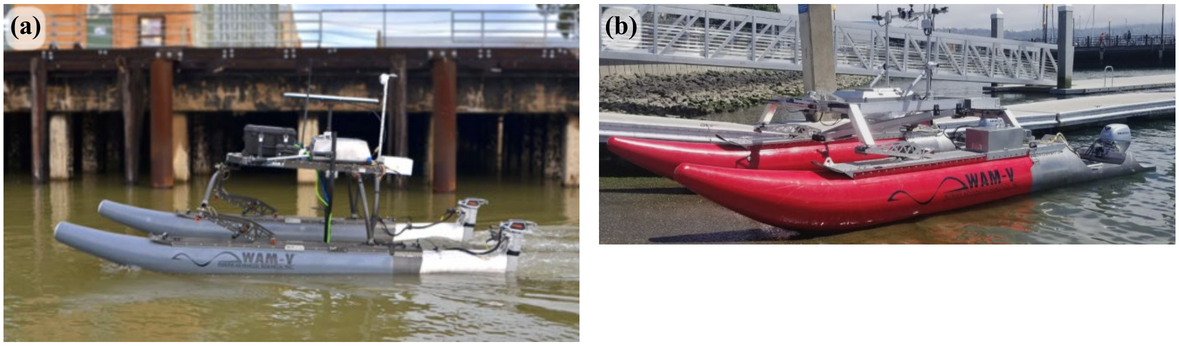

Figure 19. Marine Advanced Robotics USVs: (a) WAM-V 16, Li-ion battery powered, and (b) WAM-V 22, gasoline powered.

Photo credit: Marine Advanced Robotics Inc 2021

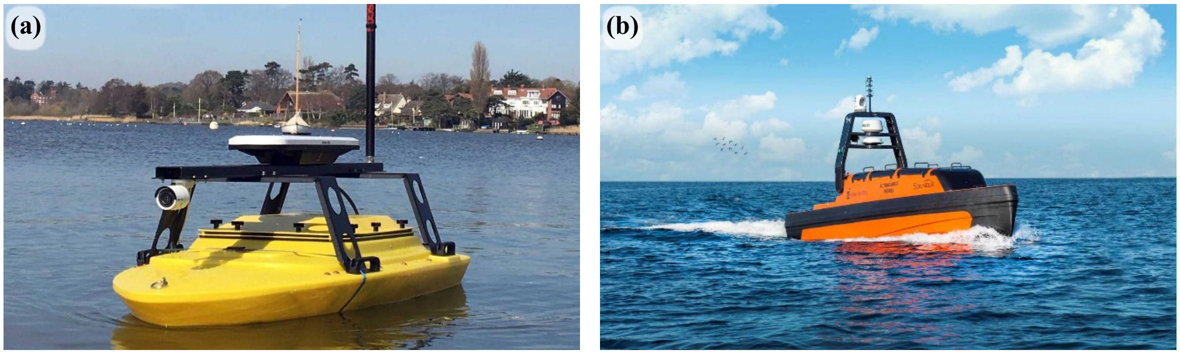

Figure 20. Kongsberg USVs: (a) **GeoSwath 4R, battery powered, and** (b) **Sounder, diesel powered.**

Photo credit: Kongsberg Maritime 2021

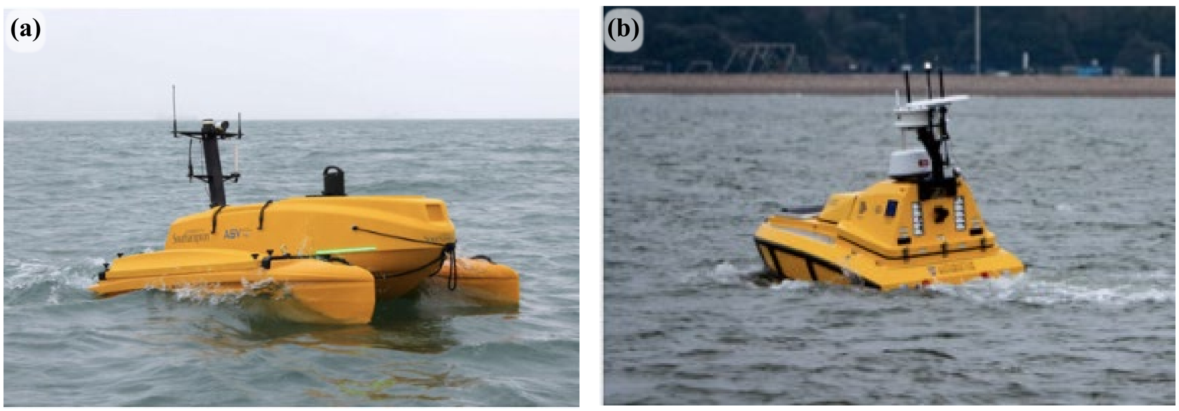

Figure 21. L3Harris USVs: (a) **C-Cat 3, battery powered, and** (b) **C-Worker 4, diesel powered.**

Photo credit: L3Harris Technologies 2021

An example of a USV powered by hybrid energy is shown in Figure 22; the SCOUT kayak, developed at Massachusetts Institute of Technology, uses solar panels to recharge a battery and power instrumentation, and a diesel generator to power an electric motor (Curcio et al. 2006).

Figure 22. Hybrid powered USV: SCOUT kayak.

Credit: Curcio et al. 2006

A variety of USVs are in commercial production that have deployment durations ranging from a few hours to a year. Deployment duration is typically linked to the travel speed and power source. For example, renewable energy can provide consistent power, but it may not be enough power for propulsion, communication, and data collection. A few USVs that demonstrate these tradeoffs are listed in Table 3.

Table 3. Energy sources and deployment duration of USVs.

Name of device	Energy source	Deployment duration
Autonaut (Autonaut Ltd. 2019)	Renewable, wave for propulsion and solar/battery for instrumentation	Multiple weeks, longest reported mission 50 days
Saildrone (Saildrone 2021)	Renewable, wind for propulsion and solar for sensors	Up to 1 year
Wave Glider (Liquid Robotics 2020)	Renewable, wave and solar	Up to 1 year
SCOUT kayak (Curcio et al. 2006)	Nonrenewable, lead acid batteries with optional 10 gal diesel fuel reservoir	8 hours at 3 knots (battery only); 44 days with diesel motor
Sounder (Kongsberg Maritime 2021)	Nonrenewable, diesel	20 days at 4 knots
C-Worker 4 ("C-Worker 4 ASV" n.d.)	Nonrenewable, diesel (2.5L/hr)	48 hours
WAM-V 16 (Marine Advanced Robotics Inc 2021)	Nonrenewable, multiple Li-ion batteries	15 hours at 5 knots; 30 hours at 3 knots
WHOI Jetyak (Kimball et al. 2014)	Nonrenewable, gasoline	8-10 hours
C-Cat 3 ("C-Cat 3 ASV" n.d.)	Nonrenewable, quick charge battery	1 day
Geoswath 4R (Kongsberg Maritime 2021)	Nonrenewable, exchangeable battery	2.5 hours at 4 knots

4.1.6 Localization Strategy

In our review of 60 unmoored, autonomous surface devices, each device was categorized by its primary localization strategy: path-planning, waypoint-holding, or drift reduction; and its predominant energy source: renewable, nonrenewable, or hybrid (Figure 23). USVs typically follow a planned path or mission, and the devices currently on the market are primarily powered by nonrenewable fuels or Li-ion batteries though some fully renewable devices exist. Buoys typically operate in a waypoint-holding mode, often with a watch-circle allowance of around 30 m in radius (e.g., WTS [Joe et al. 2017]; AMS Datamaran Mark 7 [Autonomous Marine Systems Inc. 2019]).

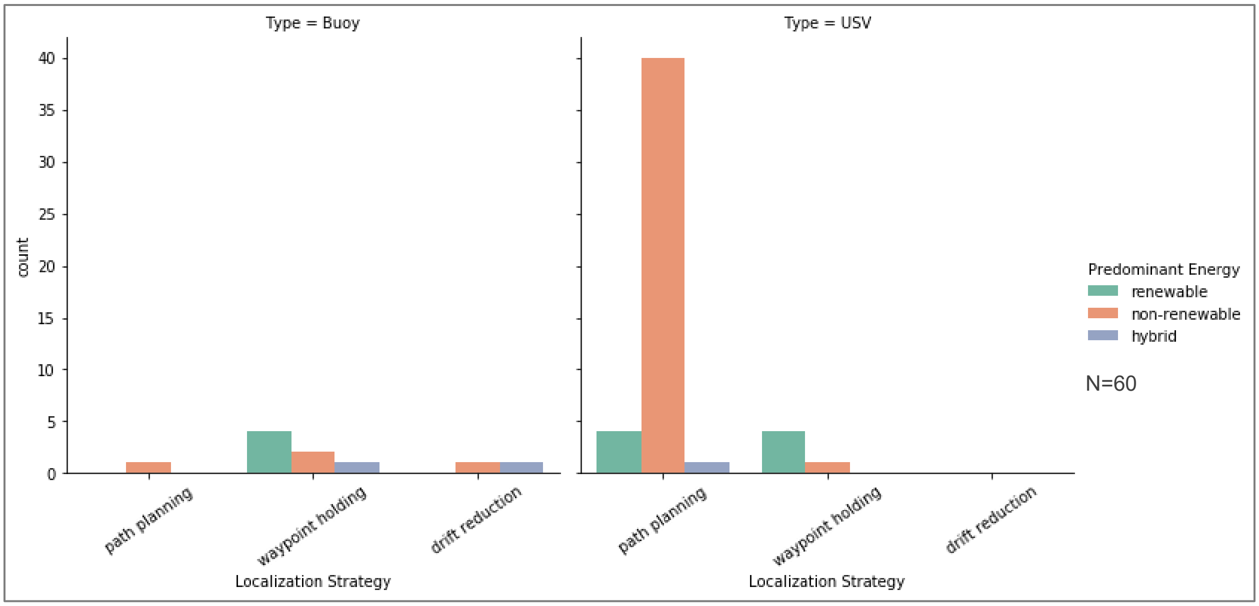

Figure 23. Predominant energy source by localization strategy for buoys and USVs.

This review suggests that significant opportunities exist for integration of renewable energy harvesting with unmoored, waypoint-holding devices. Path-planning missions traditionally require more energy for propulsion than can be provided by renewables alone, though several devices are changing that narrative (i.e., Waveglider, Autonaut, Saildrone).

4.2 Offshore Renewable Energy Systems

4.2.1 Platform Description and Physical Characteristics

Offshore Renewable Energy Systems are defined as devices that are deployed in the ocean and extract energy from renewable resources such as winds, waves, and tides.

These devices may be rated to produce power on the order of magnitude of 10 kW for powering at-sea devices such as ocean-observation platforms (Livecchi et al. 2019) and up to 1 MW and beyond for the generation of grid-scale electricity (Barter, Robertson, and Musial 2020). These devices may be suitable for various applications where the length of an ocean deployment is such that batteries and fossil fuels are infeasible because of cost, environmental factors or location, and where solar power and batteries alone are insufficient to power the application.

Mooringless station-keeping methods for offshore renewable energy systems become desirable when high water depths render the use of mooring lines unviable because of structural limitations and capital costs. Mooringless systems may also be appropriate for these platforms in the case of brief deployments (about 3 months or less), and in locations where environmental concerns or regulations do not permit mooring installations.

This analysis is divided into wave energy converters (WECs), tidal energy converters (TECs) and floating offshore wind turbines (FOWTs).

Wave Energy Converters

WECs are usually conceptualized as stationary machines that react to the forces of ocean waves. These systems are usually constrained by mooring lines or connected to the seafloor by other means. There are no real-world examples of WECs that produce power while simultaneously maintaining their location by using their own power supply.

Additionally, the fact that the WEC is unconstrained presents fundamental problems for the operation of a WEC. Almost all WEC designs react to ocean waves by being constrained in certain degrees of freedom. For example, a single body point absorber, the primary WEC archetype, reacts against a reference to the seafloor while a pitch device is held in place to allow rotation of a joint. In effect, a WEC tries to maximize relative motion, which is difficult if it is unconstrained relative to the movement of the ocean surface.

A small set of WEC designs that do not require constraints are usually referred to as Internal Reaction Mass, Self-Reacting, Inertia-Based, or Mass on Spring WECs. These designs are self-contained systems that do not have components reacting directly to waves. All system components are contained within a floating body. The primary piece of this design is a mass that will resist the movement of the enclosing hull. Power is produced while constraining the movement of the mass. One such device, conceptualized by Ocean Power Technologies, involves two internal reaction mass WECs inside of a rectangular-shaped container (see Figure 24).

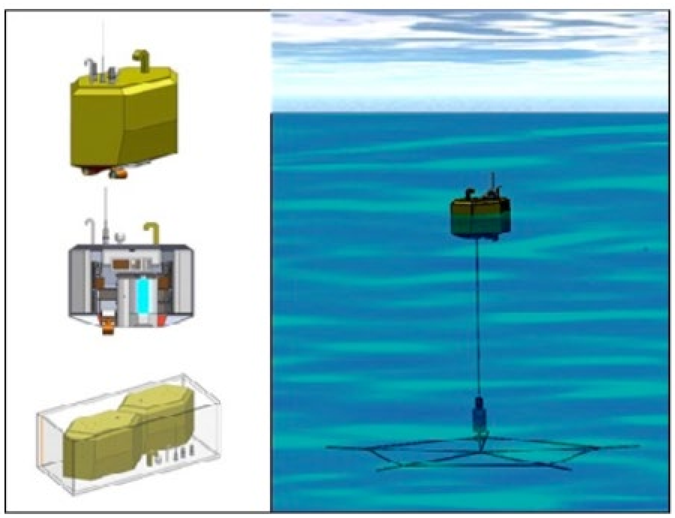

Figure 24. Ocean Power Technologies internal reaction mass wave energy converter.

Source: Stewart 2017

An alternative design explored at the University of Washington harvests energy from the relative motion between a central cylindrical nacelle and two floats (Rusch et al. 2016). This design also uses a heave plate that behaves as both a reaction mass and a drift-reducing drogue. The device, shown in Figure 25, weighs approximately 2 T, is 2.5 m long, and uses a heave plate line length of 57 m.

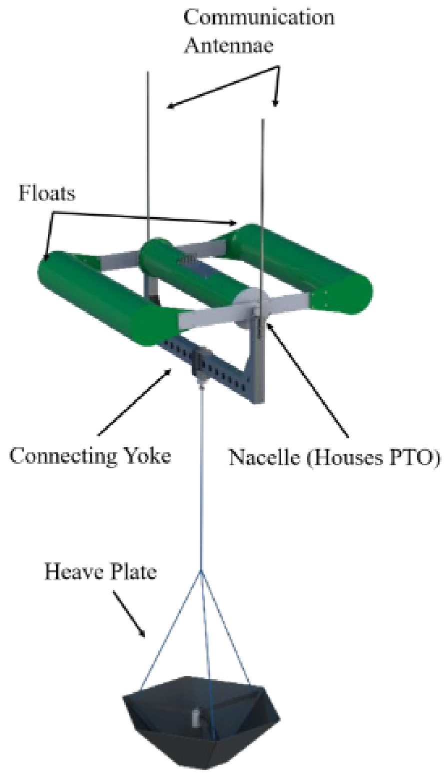

Figure 25. Heaving point absorber concept.

Source: Rusch et al. 2016

The Halona WEC is a floating Oscillating Water Column (OWC) that is designed to function as an autonomous underwater vehicle (AUV) docking platform (see Figure 26). The device consists of a central spar, 8 m in height and 1.38 m in diameter, and protruding wave guides, 3 m in height and 1.5 m in width, which also function as wings that act as drogues. The WEC has a draft of 6 m and a dry weight of 5.67 T. The WEC extracts energy as the relative motion between the water surface and the body of the WEC forces air through a wells turbine within a chamber. This oscillation is amplified using a Helmholtz resonant chamber design; by altering the ratio of the chamber diameter, the waveguide length, and the wave guide angle, the volumetric flow rate of the OWC may be optimized (Ulm et al. 2020).

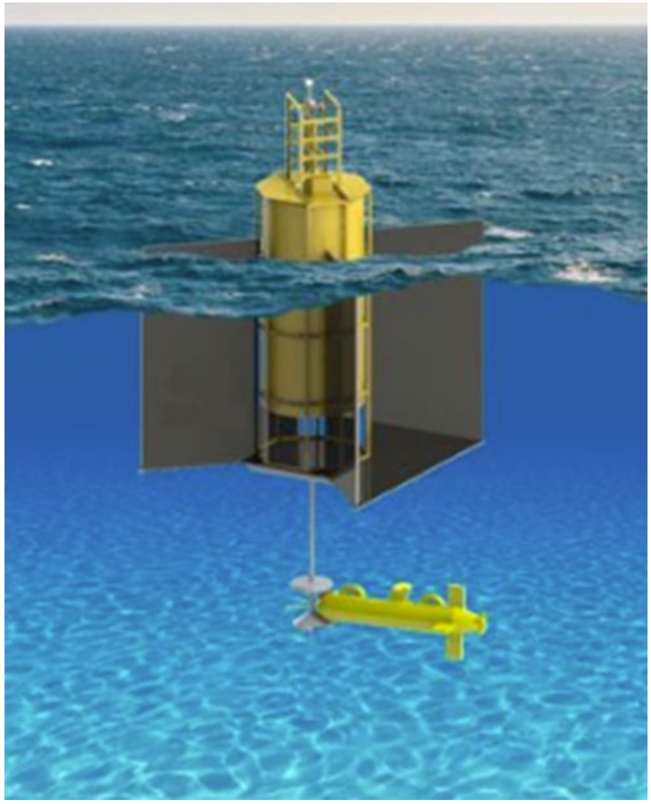

Figure 26. Halona OWC WEC and AUV docking platform.

Source: Ulm et al. 2020

Tidal Energy Converters

The literature on mooringless TECs is sparse because of the requirement for a counter force to the thrust generated by an energy-harvesting tidal turbine, which is usually enacted by a mooring system for floating TEC concepts. A novel topology proposed by researchers at Toaki University in Japan builds upon the sailing-type offshore wind farm literature discussed by Suzuki (2005) by employing very large sails for propulsion (Terao, Watanabe, and Wakita (2007); Figure 27). The platform consists of a large catamaran hull measuring approximately 300 m in length and 200 m in width. Terao, Watanabe, and Wakita (2007) conducted a parametric study to optimize the turbine diameter by increasing hull speed while maintaining a low hull resistance.

Figure 27. Conceptual schematic of a sailing tidal current platform.

Source: Terao, Watanabe, and Wakita 2007

Floating Offshore Wind Turbine Platforms

FOWT platforms most commonly use spar, semi-submersible, or tension-leg platform designs, as shown in Figure 28. As such, FOWT platforms typically use mooring systems for station-keeping (Barter, Robertson, and Musial 2020). As of 2018, only eight pilot floating offshore wind farms have been installed globally, typically using wind turbines of the generating magnitude of 1–2.5 MW (U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy 2019). Future projects under development are targeting the deployment of machines rated at 3–15 MW, typically featuring rotors 130–170 m in diameter and hub heights of 160–200 m (Barter, Robertson, and Musial 2020).

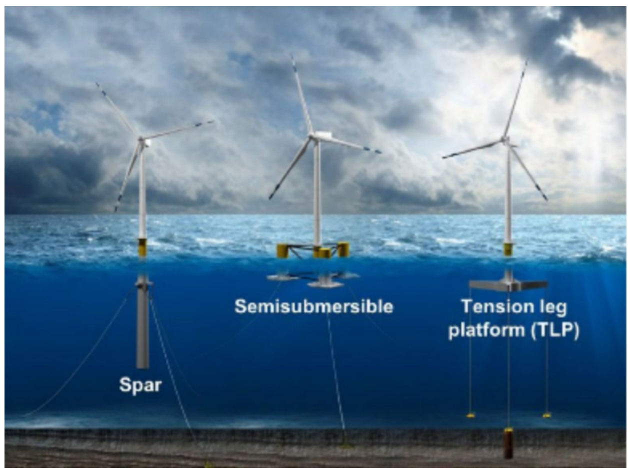

Figure 28. Moored FOWT platform archetypes.

Source: Barter, Robertson, and Musial 2020

Because of the nascent nature of floating offshore wind platform technology, the research of mooringless floating offshore wind turbine platforms has been limited largely to theoretical designs and experimental studies; no full-scale mooringless floating offshore wind turbine platforms currently exist. There is, however, literature concerning single turbine platforms (Xu et al. 2021; Sim, Shin, and Kumar 2019) and larger structures, including a conceptual 40 MW open-ocean platform (Alexander 2019) and work conducted on sailing-type Very Large Floating Structures (VLFSs) (Manabe et al. 2008; Suzuki 2005; Terao, Watanabe, and Wakita 2007).

The single turbine platform investigated by Xu et al. (2021) is based on the semi-submersible archetype, with hub height and base dimensions as shown in Figure 29. This platform has three side columns and one central column of 18 m and 22 m in major diameter, respectively. The total height of the footings is 20.8 m, the total weight of the platforms is 8130 T, and the operating draft is 15.1 m. A 5 MW wind turbine model is selected as the base design.

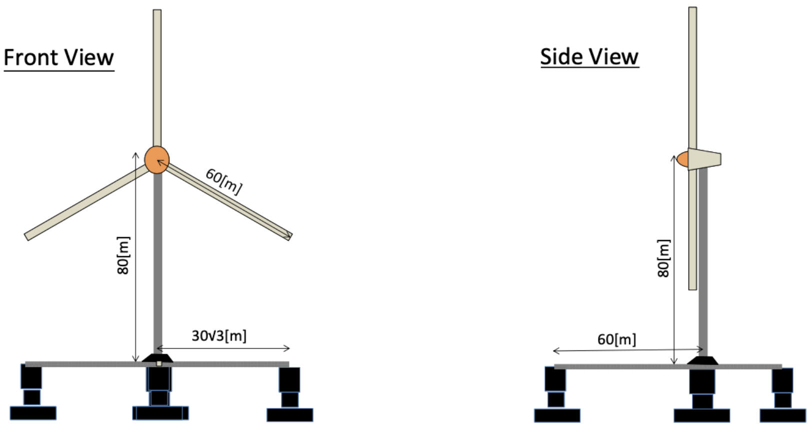

Figure 29. *Semi-submersible wind turbine platform dimensions.*

Source: Xu et al. 2021

Sim, Shin, and Kumar (2019) investigated a toroidal-shaped, honeycomb floating structure for drift reduction using flapping plates (Figure 30). Although the full-scale model dimensions and final wind turbine payload are not specified, the constructed prototype has an outer diameter of 900 mm, height of 170 mm, draught of 40 mm and mass of 11 kg.

Figure 30. *Drift-reducing floating structure prototype.*

Photo credit: Sim, Shin, and Kumar 2019

A theoretical design for a 40 MW free-floating wind energy turbine, the Hi-Seas, is presented by Alexander (2019) and shown in Figure 31. The Hi-Seas uses a large pyramidal truss structure to support a downwind turbine. The turbine hub height is 170 m and the rotor diameter is 250 m. The width and depth of the structure, measured between the floats, is 300 m and 250 m, respectively. The truss structure is connected to stabilizer spheres, each measuring 27 m in diameter and filled with water, located 100 m below the water surface.

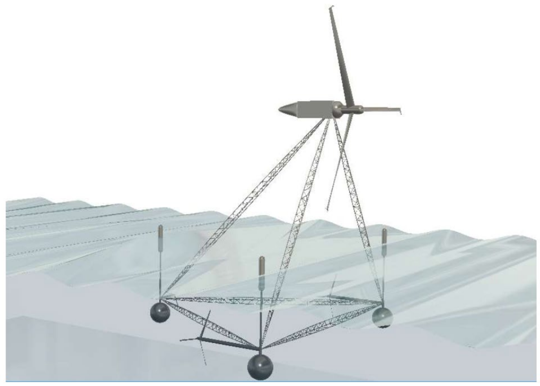

Figure 31. Hi-Seas wind energy conceptual superstructure.

Source: Alexander 2019

The development of a sailing-type offshore wind farm, consisting of a VLFS with 11 wind turbines and 4 sail units, is detailed by Manabe et al. (2008) and depicted in Figure 32. The platform measures 1.88 km long by 70.2 m wide, is 32.0 m deep, and has an operating draught of 20.0 m.

Figure 32. Sailing-type offshore wind farm.

Source: Manabe et al. 2008

4.2.2 Applications of Platforms

Floating offshore wind platforms are used for the generation of grid-scale electricity, typically on the scale of 3–15 MW. Smaller platforms designed for PBE applications may be rated up to 10 kW. Applications for these platforms may include the following (Copping et al. 2020):

- AUV charging
- oceanographic sensor powering
- mobile aquaculture operations
- communications and security

4.2.3 Operating Environments

Mooringless WECs have the potential to be deployed in areas where sufficient and reliable wave energy is available to power specific applications, and where mooring is not an option; each condition needs to be evaluated on a case-by-case basis. In parallel to the preparation of this report, another PBE task team is actively researching opportunities to use WECs in the deep ocean across the globe, while others have been investigating the use of WECs in more targeted areas such as the Arctic, for which any further discussion of wave power availability and use is hereby reserved to the publication of their findings.

The catamaran hull TEC platform described by Terao, Watanabe, and Wakita (2007) is intended to be resilient relative to and even take advantage of typhoons and associated ocean currents. In general, TEC platforms are designed to operate in regions with prevailing ocean currents, such as the Florida Gulf (e.g., OceanBased (2021)).

Mooringless floating offshore wind platforms may be deployed in deep water exceeding 50 m in water depth. Deep water locations for deployment of floating offshore wind farms range from country-specific regions such as the Economic Exclusion Zone of Japan (Suzuki 2005) to greater geographic regions such as between the 40th and 60th Latitudes (Alexander 2019).

4.2.4 Predominant Energy Sources and Consumption

In WECs, a power take-off (PTO) mechanism converts the motion of the WEC components into usable power using primarily mechanical, electric, or hydraulic mechanisms, or combinations thereof. The PTO is usually coupled to some type of energy storage method such as batteries and flywheels. To power station-keeping systems for WECs, such as jets or propellers, the wave energy would first have to be transformed into an intermediate form of energy. For example, the electrical power produced by a PTO system could be stored in batteries, which in turn could power a propeller when necessary.

As for the sailing-type TEC and FOWT platforms (Terao, Watanabe, and Wakita 2007; Suzuki 2005; Manabe et al. 2008), propulsion is achieved through the use of very large sail structures, thus using wind energy directly without the need to harvest and store it. In contrast, the concepts proposed by Xu et al. (2021) and Alexander (2019) rely on active thrusters and thus convert a portion of their total energy generated to propulsion. The majority of the FOWT platforms proposed use hydrogen as the primary form of energy storage.

4.2.5 Localization Strategy

In this section, the operating principles and effectiveness of various localization strategies used by the investigated mooringless WEC, TEC, and FOWT platforms are discussed.

Drift Reduction

Heave Plate WECs

A numerical simulation presented by Rusch et al. (2016) estimates the power requirements for a novel station-keeping point absorber designed by Columbia Power. The drift forces were evaluated with two time-domain representations of a Pierson-Moskowitz and a Jonswap spectrum, each characterized by a 2.5 m significant wave height and 7 s peak period. The WEC experienced average drift rates of 0.13 m/s and 0.14 m/s for the Pierson-Moskowitz and JONSWAP spectra, respectively. The amount of thrust necessary to counter these velocities was also estimated. Using an approximation of 2.5 W/N of force, they calculated that the device would require 430 W to station-keep. Because the power output estimation of the device was 480 W for this condition, the article suggests that station-keeping, while producing the necessary power to both station-keep and power onboard applications, might be difficult to achieve.

Details about the station-keeping abilities of the Ocean Power Technologies internal reaction mass WEC, shown in Figure 24, were not found in the literature. However, the design was developed in response to a Navy Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Transition Program (Frost 2012), which required that devices could "…be used in all depths of water and achieve tactical anti-submarine control of an area for several weeks. The U.S. Navy has identified the need for a persistent, easy to deploy, anchorless active sonar system that contains a float or small craft for suspension of the sonar arrays…." This suggests that the drift-reduction capabilities of the Ocean Power Technologies WEC concept would at least allow for the device to maintain station over a large watch-circle of several kilometers for deployment periods of approximately 20 days or more. Furthermore, in a distribution statement released by the Navy, the Ocean Power Technologies buoy is described as self-propelling and equipped with electric thrusters to effect buoy transit or station-keeping (Stewart 2017).

Flapping Plate FOWT

The addition of passive oscillating flaps to the side of a free-floating offshore wind turbine platform is investigated by Sim, Shin, and Kumar (2019). These flaps are arranged radially around a honeycomb toroidal floating structure secured by an aluminum frame and they generate thrust upon excitation by wave action. The flaps act to reduce the drift of the platform and may be configured to act in a predominant direction (see Figure 33).

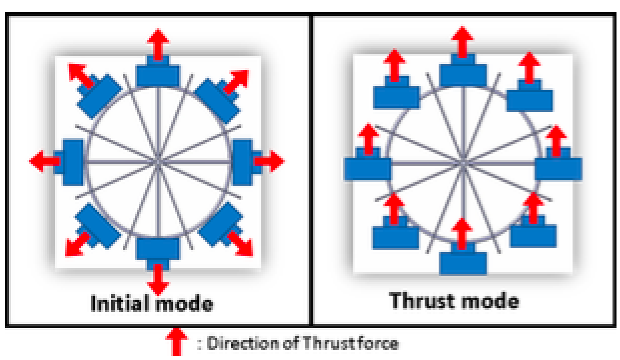

Figure 33. Generation of thrust by flapping plates.

Source: Sim, Shin, and Kumar 2019

As an incident wave excites a flap, thrust is generated in the direction of the flap's mounting point, resulting in floater drift velocity in the opposing direction. Flaps are chosen over foils because of their broad response over a wide frequency range, despite their lower generated thrust. The flaps are attached to the platform by an elastic plate in a cantilever configuration (see Figure 34).

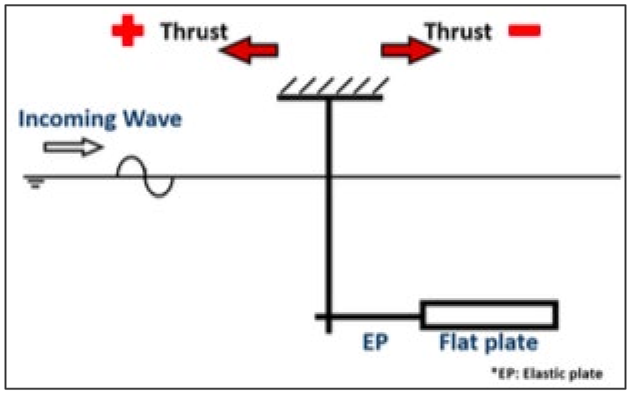

Figure 34. Thrust generation of flaps.

Source: Sim, Shin, and Kumar 2019

The criterion for effective station-keeping of the passive oscillating flaps within a tank test environment was set at 15% of water depth for approximately 2 min of wave excitation. Subject to regular waves of varying periods, the platform is able to fulfill this criterion; under irregular wave excitation, the platform surge is highly variable, but it performs better in "thrust mode" than in "initial mode," indicating that the addition of flaps improves the platform's station-keeping ability. The comparison of the initial and thrust modes are made in a qualitative sheltered sea test, yet, preliminary results show promise for the thrust mode configuration. When the passive oscillating flaps are arranged to station-keep against the prevailing wave direction, overall platform drift is reduced. Although this method shows promise, further results are required to characterize its effectiveness under real-sea conditions. The proposed passive oscillating flap method has yet to be deployed on a full-scale free-floating wind turbine platform.

Path-Planning

Drogue WEC

Halona WEC end-users require a platform capable of moving with a background flow pattern that observes AUV operating-scale areas of 225 km^2 and larger regions of up to 24,000 km^2. The platform operates by using minimal mechanical energy via a control surface to direct its drift across different geographic regions; regional oceanic current maps are used to determine an optimized path to navigate from one region to another. In this way, the platform is able to navigate predetermined trajectories, such as the paths of migrating fisheries (Ulm et al. 2020).

Sailing-Type TECs and FOWTs

The catamaran sailing-type tidal platform, proposed by Terao, Watanabe, and Wakita (2007), is designed to minimize total hull and turbine resistance while maximizing advance speed, thereby improving sailing performance and long-term operation within areas of high wind forces (with corresponding nominal wind speeds >14 m/s).

The sailing-type VLFS offshore wind farm maintains its relative position by moving in a switch-back motion (Manabe et al. 2008). Propulsion is generated by large sails at the extremities of the platform; the sail structures produce lateral lifting forces which in turn counter the thrust forces on the wind turbines (Figure 35). An advantage of the sailing-type offshore wind farm is its ability to be relocated in the event of poor weather such as storms or to travel to more energetic wind environments. As such, this platform is considered to follow a path-planning localization strategy. Because of the vast size of the platform and extensive operating area, the VLFS platform need not maintain station within a narrow watch-circle.

Figure 35. Large sails used to counter the thrust of wind turbines.

Source: Manabe et al. 2008

Waypoint-Holding

The platforms presented by Xu et al. (2021) and Alexander (2019) both attempt to station-keep by counteracting the thrust force of the oncoming wind by the use of underwater thrusters.

Semi-Submersible Wind Turbine Concept

The semi-submersible platform presented by Xu et al. (2021)maintains station by the use of azimuth thrusters mounted on the bottom of each of its three outer columns that counteract the thrust force of the oncoming wind (Figure 36). The power generated by the wind turbine when exposed to a range of wind speeds is compared to the power consumed by the thrusters through numerical modeling. The simulation results indicate that a power ratio of 0.5 may be attained, such that the net power generation is positive. This is achieved by optimizing the azimuth angle of the thrusters to produce the required thrust force to maintain station.

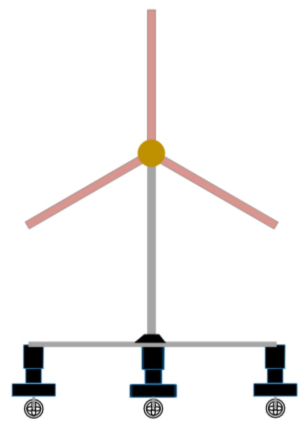

Figure 36. ***Semi-submersible platform dynamically positioned using azimuth thrusters.***

Source: Xu et al. 2021

During extreme wind and wave conditions, when the wind turbine would not be operational, the azimuth thrusters require an active power source to maintain station. The feasibility of using onboard hydrogen energy storage is investigated to facilitate this task. The study shows that maintaining station in idle wind turbine scenarios is indeed possible, however, the power ratio is worsened to approximately 0.8. Considering this, the turbine is recommended to be deployed in sites of low tidal currents, but in any case, this method of power generation is still a net positive.

Large Wind Turbine Open-Ocean Concept

The extremely large FOWT platform conceptualized by Alexander (2019) uses a 40 MW rated wind turbine to power an electrolyzer that produces liquid hydrogen for on-board storage within its nacelle. The movement caused by the wind thrust force is counteracted by using two large propellers, 70 m in diameter, that offset surge displacements, and one propeller, 30 m in diameter, that correct yaw misalignment in cross currents of up to 1.6 m/s.

This station-keeping method relies on an active control of thrusters making use of an interesting phenomenon arising from the thrust generated in different mediums; because water is approximately 1,000 times more dense than air, the movement of large quantities of water at relatively low velocities, is claimed to be sufficient to counteract the thrust of the wind turbine. To maintain station, the three propellers require approximately 10% of the power generated by the wind turbine at its rated speed (Figure 37).

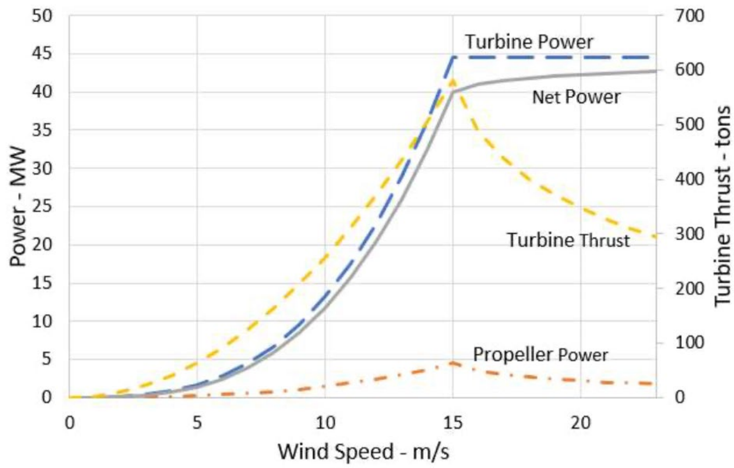

Figure 37. Propeller power consumption compared to wind turbine generated power (left axis) and turbine thrust (right axis).

Source: Alexander 2019

4.3 Unoccupied Underwater Vehicles

4.3.1 Platform Description

Methods of mooringless station-keeping can be applied to UUVs to perform a variety of scientific tasks in the open ocean. UUVs allow for sensing of the coastal and open ocean at much higher spatial and temporal resolutions, as well as at lower cost, than using techniques that rely on large crewed ships or moorings. Common UUV platforms include remotely operated vehicles (ROVs), AUVs, gliders, and profiling floats.

Considering that ROVs involve the use of a tether, the methods of mooringless station-keeping for UUVs, described beyond this subsection, will focus on the subtypes of AUVs, gliders, and profiling floats. Between these different subtypes, there is a large difference in controllability, endurance, speed, and cost.

Remotely Operated Vehicles

An ROV is controlled by a human operator through a tether that links the submersible to a control system external to the submersible vehicle. The horizontal and vertical motion of the submersible can be controlled but is limited by the length of tether used. Examples of commercially available ROV platforms are shown in Figure 38.

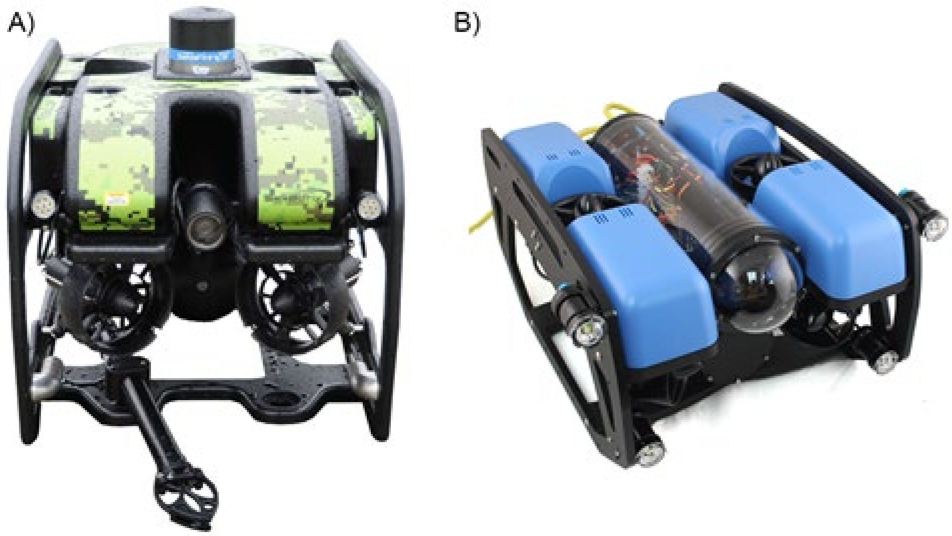

Figure 38. Examples of commercially available ROVs: A) Teledyne vectored Little Benthic Vehicle; and B) Blue Robotics BlueROV2.

Autonomous Underwater Vehicles

AUVs are self-contained vehicles that use an active propulsion/steering system that is controlled using onboard electronics with no, or limited, human interaction. These vehicles are capable of controlling horizontal and vertical motion. Mission durations are typically measured in hours, during which time a vehicle can travel tens of kilometers. Examples of commercially available AUV platforms are shown in Figure 39.

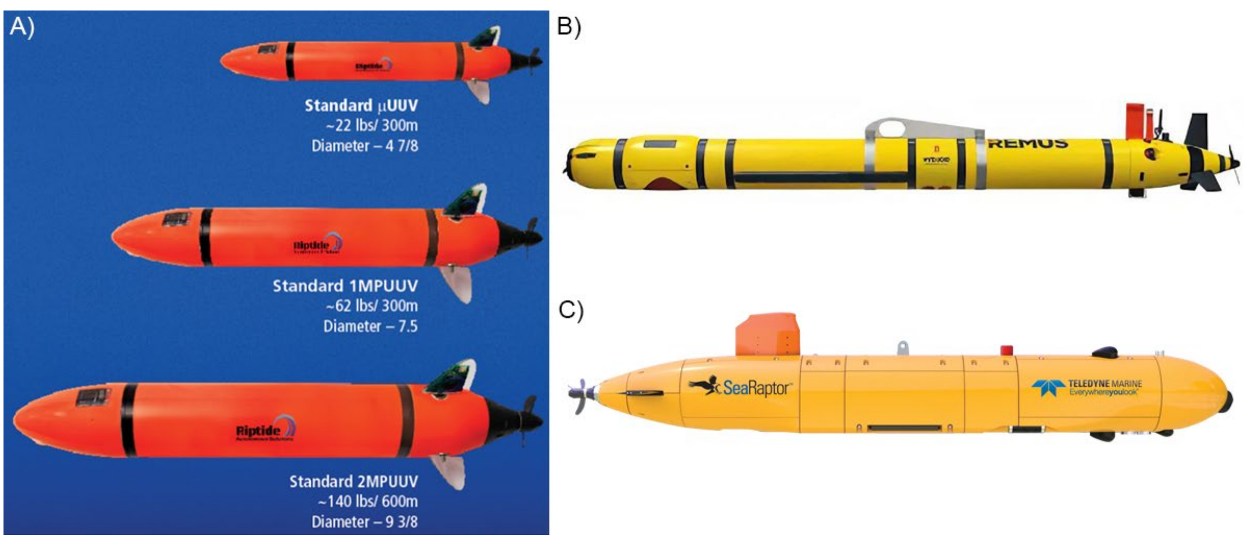

Figure 39. Examples of commercially available AUVs: A) BAE Systems Riptide family of AUVs; B) Kongsberg Remus 600; and C) Teledyne SeaRaptor AUV.

Gliders

Gliders are self-contained UUVs that use buoyancy control to provide vertical propulsion. Hydrodynamic fins propel the vehicle forward as it sinks and rises. The elevation of the vehicle is typically manipulated by moving a mass within the vehicle, often the battery, that result in a buoyancy change. Mission durations can be several weeks to over a year, during which time a vehicle could travel thousands of kilometers. Examples of commercially available glider platforms are shown in Figure 40.

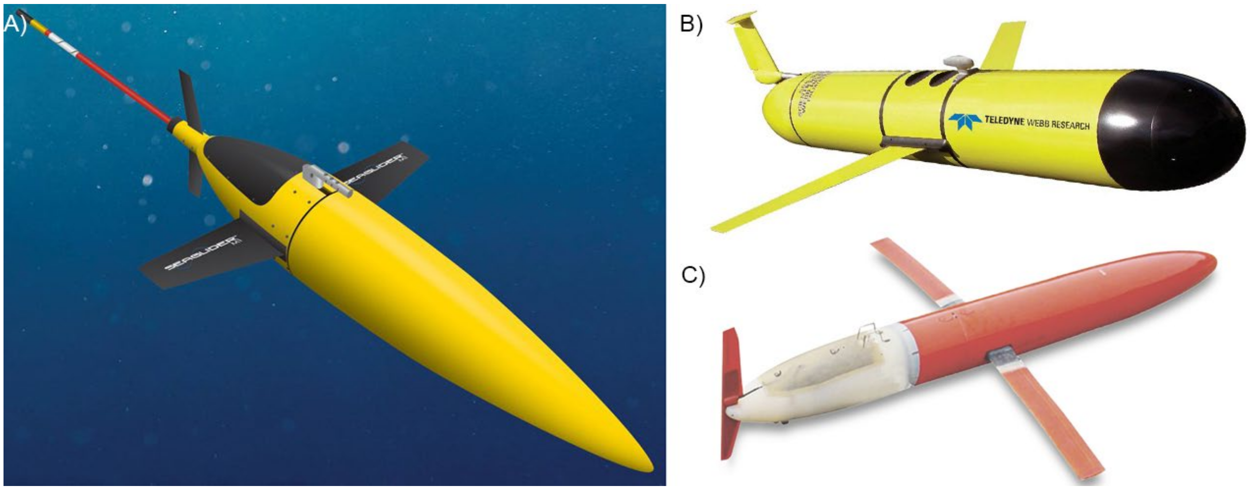

Figure 40. Examples of commercially available gliders: A) iRobot Seaglider; B) Teledyne Slocum G3 Glider; and C) Bluefin Robotics Spray Glider.

Profiling Floats

Profiling floats are self-contained UUVs that use buoyancy control to provide vertical propulsion. They do not have any means of horizontal propulsion and are free to drift with ocean currents. Mission durations can be around three to five years. Examples of commercially available profiling floats used in the international observation program Argo are shown in Figure 41.

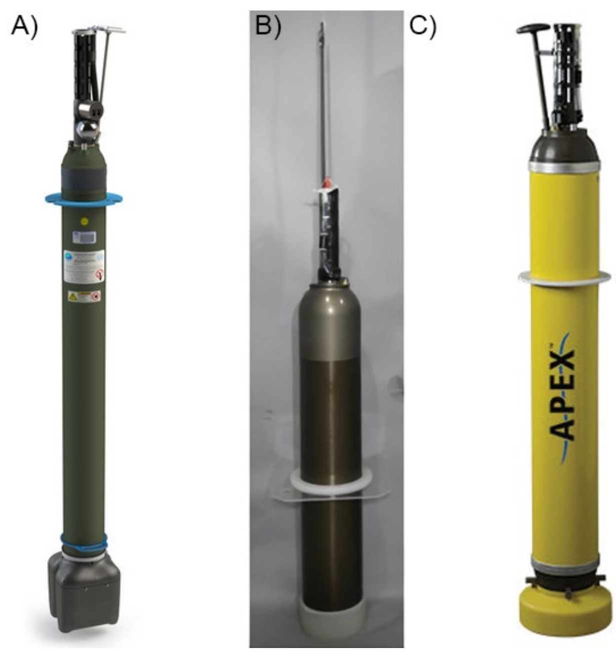

Figure 41. Examples of commercially available profiling floats used in the Argo array: A) Sea-Bird NAVI; B) Scripps Institution of Oceanography SOLO-II; and C) Teledyne APEX.

4.3.2 Physical Characteristics

There are several different genera of UUV, including ROVs, AUVs, gliders, Large UUVs, and Extra Large UUVs (XLUUVs). While a glider can be 1–2 m in length and 50 kg in weight, the Orca (Figure 42), one of the XLUUVs being manufactured by Boeing, is 15.54 m long without payload and 26 m long with the payload section (Boeing 2020). The Orca's payload bay can hold more than 7000 kg of dry weight.

Figure 42. Photo of the Orca, an XLUUV.

Credit: Boeing 2020

The depth rating of AUVs has also increased significantly over the last decade. For example, the Poseidon 6000 AUV by Qingdao Hisun has a depth rating of 6000 m. For reference, the Poseidon measures 7 m in length, and weighs 3,500 kg (Qingdao Hisun Ocean Equipment Company n.d.).

4.3.3 Applications of Platforms

UUVs are used for a wide range of activities in the ocean, and certain platforms are better suited for some applications than others based on their unique characteristics. The differences between the applications of each UUV subtype depend on the tradeoff between the degree to which the path of the vehicle needs to be controlled and the longevity of the deployment. Profiling floats, such as those that form the Argo array, are primarily useful for sensing ocean conditions given their ability to operate for several years once deployed, whereas AUVs can be used for a more diverse range of applications that include not only sensing ocean conditions but activities such as natural resource exploration, animal detection, optical/acoustic imaging, and many others.

4.3.4 Operating Environments

Given the diversity of the subtypes, UUVs are operated throughout the entire ocean. This includes coastal waters, open ocean, and under glacial ice.

4.3.5 Predominant Energy Sources and Consumption

A typical UUV uses a battery that powers various subsystems including the propulsion, navigation, sensing, and communication systems. Some UUVs also use renewable energy in the form of ocean gradients, primarily thermal, for this purpose. One such example is the Slocum (Webb, Simonetti, and Jones 2001), a glider-type UUV that uses ocean thermal gradients to extract energy that can be used for propulsion. By using energy extracted thermal gradients, this 3.2 m long UUV can achieve a theoretical operational range of 40,000 km. However, the energy requirement for powering autonomous sensing systems in UUVs has been increasing over time because of increasing sensing needs.

The energy needs depend on the size of the UUVs. For smaller UUVs, the maximum onboard energy storage can be several kilowatt-hours, while the Boeing Orca uses an 18 kW battery to power the payload bay.

A review paper discussing the use of gliders for ocean research, by Rudnick et al. (2004), provides information about the battery capacity for three gliders common at the time of publishing: Seaglider (13 MJ), Spray (8 MJ), and Slocum (10 MJ). The authors describe the general operation of gliders to approximate the power requirements. For a typical glider the following information characterizes the order of magnitude of typical vehicle and mission properties:

- Horizontal speed ~ 25 cm/s
- Glide slope ~ 2-4
- Dive depth ~ 1 km
- Diver duration ~ several hours
- Energy for buoyancy change ~ 10 kJ

As a result, a glider typically draws an average of 0.5 W of power for propulsion for the given conditions.

Profiling floats tend to use approximately similar amounts of power per profiling cycle as gliders. Gordon (2017) reported that for the different models of core Argo floats, which are equipped with lithium batteries, the range of energy use per profile is between 10 and 16 kJ. The total battery energy, at about 4 to 5 MJ, is typically less than would be carried by a glider. The report also detailed the energy budget for a profiling float, the Teledyne Apex, allotted to various subsystems including oxygen and nitrate sensors (see Table 4). For comparison to gliders, the energy used by the buoyancy engine is about 4 kJ per profile compared to the value of 10 kJ stated for gliders.

Table 4. Energy breakdown by components for a Teledyne Apex float averaged over 374 profiles.

Excerpt from Gordon 2017, Appendix C

Component	Percentage of Energy (%)	Mean Energy per Profile (kJ)
Buoyancy Engine	28.9	4.01
Primary Controller	10.0	1.39
Localization and Telemetry	13.9	1.94
Nitrate Sensor	21.3	2.97
Oxygen Sensor	0.6	0.09
CTD Sensor	20.2	2.80
Battery Self-Discharge	5.0	0.70
Total	**100.0**	**13.90 kJ**

4.3.6 Localization Strategy

The localization strategy of ROVs and AUVs is primarily a path-planning one, although with proper control systems these vehicles may also apply a waypoint-holding localization strategy. Path-planning strategies are also common for gliders and are being researched for profiling floats, the latter of which do not otherwise apply any localization strategies and are instead allowed to drift freely at a predetermined depth.

Station-keeping of UUVs is very challenging because of the complex underwater environment and highly nonlinear effects of autonomous control because of the hydrodynamics in the ocean. Robust control algorithms and active controller design have been identified as the key research areas for station-keeping of UUVs, mainly for ROVs and AUVs, and a large number of recent publications have reported progress on this effort, including algorithm development, numerical simulation, laboratory demonstration, and sea trials.

A thorough review of robust control algorithms for ROVs is presented by Azis et al. (2012), including multiple control methods such as using a linear–quadratic regulator, proportional-integral-derivative (PID), sliding modes, fuzzy methods, and neural networks. A summary of the challenges in conventional station-keeping controllers that use highly complex sensor fusion algorithms is presented by Woods et al. (1998), as well as a design for a stereoscopic ranging system to improve conventional controllers. Antonelli et al. (1999) developed an adaptive control strategy for AUV path-planning and reported improved experimental results. Smallwood and Whitcomb (2004) evaluated several model-based control designs for underwater vehicles including a PID controller, an exact linearizing feedback controller, and a controller without exact linearization. The authors reported that the systems exhibited robust performance with respect to sensor noise and demonstrated that trajectory performance is highly sensitive to the accuracy of model parameterization. The importance of incorporating accurate vehicle parameters into the control system as feedback is likewise highlighted by De Souza and Maruyama (2007) in a study that evaluated decentralized control techniques, including linear PID, feed-forward strategy, and sliding mode, using a fully coupled and nonlinear underwater vehicle model.

While discussions about using adaptive controllers to overcome the complex and highly nonlinear nature of UUV station-keeping have been present in the literature for many years (Craig, Hsu, and Sastry 1987; Cristi, Papoulias, and Healey 1990), recent improvements in machine learning techniques have led to an increased interest in them. For example, Bessa, Dutra, and Kreuzer (2008) proposed and implemented an adaptive fuzzy sliding mode controller to better regulate the depth of underwater robotic vehicles. Later, Bessa, Dutra, and Kreuzer (2013) used a sliding-mode compensator with fuzzy gains for thruster estimation, which showed improved performance over the commonly-adopted feed-forward strategy. Finally, Hassanein et al. (2016), developed indirect adaptive controllers for AUVs based on a Hybrid Neuro-Fuzzy Network approach, which showed a robust control performance under simulated and experimental conditions.

Profiling floats and gliders typically rely on passive control, using changes in buoyancy, with the primary difference being that profiling floats can only use the change in buoyancy for vertical propulsion while otherwise passively drifting in the ocean current, while a glider uses hydrodynamic fins to obtain forward propulsion from the vertical displacement and to provide steering for the vehicle, by shifting the center of gravity within the UUV. Both of these types of UUVs travel at much slower speeds than typical AUVs. For this reason, there is often a need to deploy more gliders or profiling floats than would be required to sample a physical phenomenon using AUVs. For example, the Argo program uses an array of approximately 4,000 profiling floats to collect temperature, salinity, and pressure data throughout the world’s oceans (Roemmich et al. 2019). Alvarez, Garau, and Caiti (2007) investigated combining networks of profiling floats and gliders to conduct adaptive sampling of the ocean. In the research conducted, the network of profiling floats served to capture large and slow scale variability while the small- and fast-scale variability was captured by the network of gliders. The researchers used a genetic algorithm for the path-planning of the vehicles in the glider network and conducted simulations to investigate the benefits of combining these two networks. The results indicated that there was a substantial improvement in the quality of the field derived from the combined measurements taken by the profiling float and glider networks.

Once a profiling float, like those composing the Argo array, has been deployed (Figure 43), it will adjust its buoyancy until it achieves neutral buoyancy at a target depth where it will drift with ocean currents for a period of several days. After a predefined amount of time, the profiling float will descend to a deeper depth before ascending back to the surface while taking measurements from the sensors. Once on the surface, the profiling float will upload the data collected using satellite communications before descending back to the target drifting depth. This process continues until the profiling float no longer has sufficient energy to return to the surface, currently around six years, and the profiling float sinks to the seafloor.

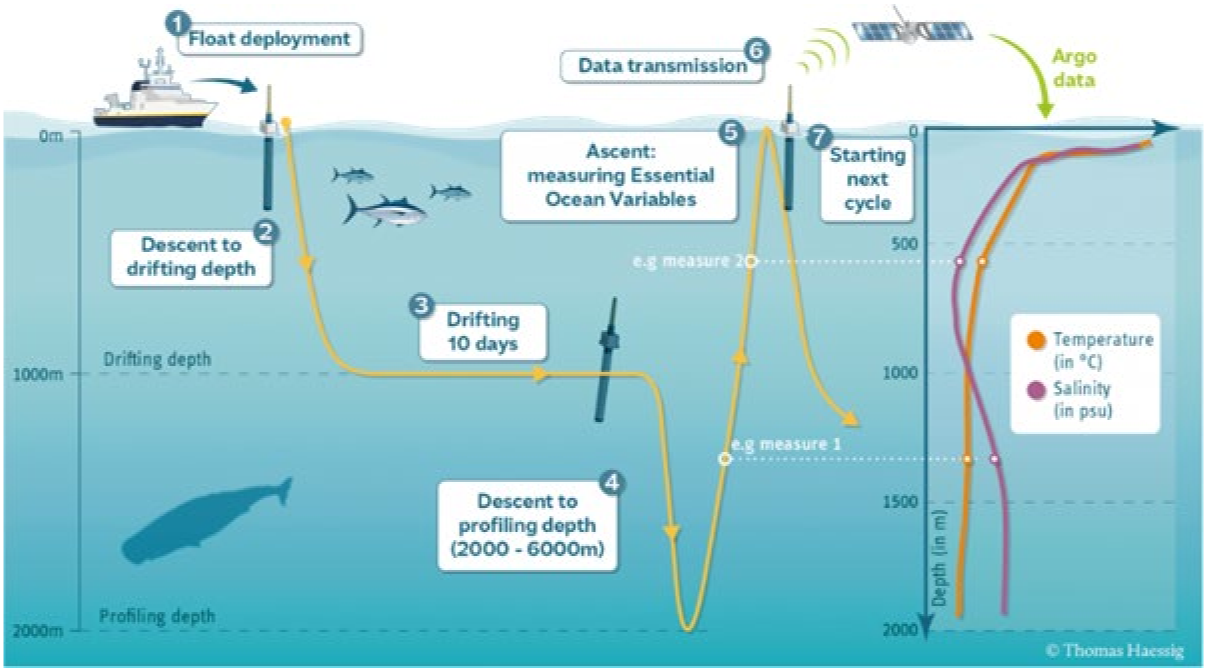

Figure 43. Schematic showing the typical profiling cycle for the profiling floats composing the Argo array.

Credit: Scripps Institution of Oceanography, UC San Diego 2020

As mentioned earlier, gliders also use changes in buoyancy for propulsion and feature hydrodynamic fins for steering. During a profiling cycle conducted by a glider (Figure 44) the vehicle will use an inertial measurement unit, pressure sensor, and altimeter to navigate under water through a process known as “dead reckoning,” where the direction and distance traveled by the vehicle is estimated from these measurements. When the vehicle resurfaces it will use an onboard GPS receiver to obtain the true distance and direction traveled. The difference between the estimated and actual distance and direction traveled is used to estimate the depth-averaged current. Considering that information gathered by UUVs is routinely uploaded via satellite-based communications, it is possible to use the depth-averaged currents measured by nearby vehicles to guide the path-planning for each of the vehicles in a network.

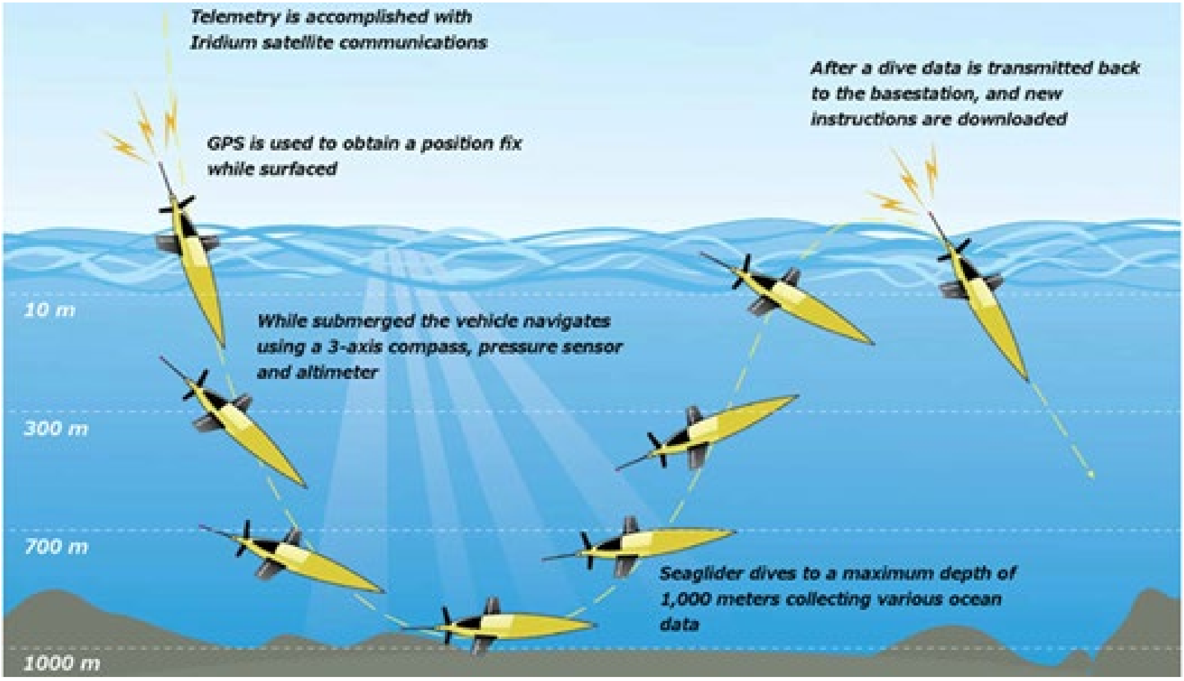

Figure 44. Schematic showing the typical profiling cycle for a glider type UUV

Credit: Kongsberg Seaglider

Gliders tend to move slowly at speeds of up to about 0.5 m/s, which can be well below the speed of ocean currents at the surface. However, the depth-averaged current can be considerably lower (Figure 45), thus allowing a glider to make headway against ocean currents. The slow speed is what allows gliders to achieve considerably higher endurances than faster AUVs because of the considerably lower drag acting on the vehicle. For an AUV travelling at a speed of 2.5 m/s the Reynolds number is on the order of 107, while it is only around 106 for a glider, and as a result the glider requires less than 1% of the propulsion power (Hodges and Fratantoni 2009). This allows gliders to obtain endurances of several months.

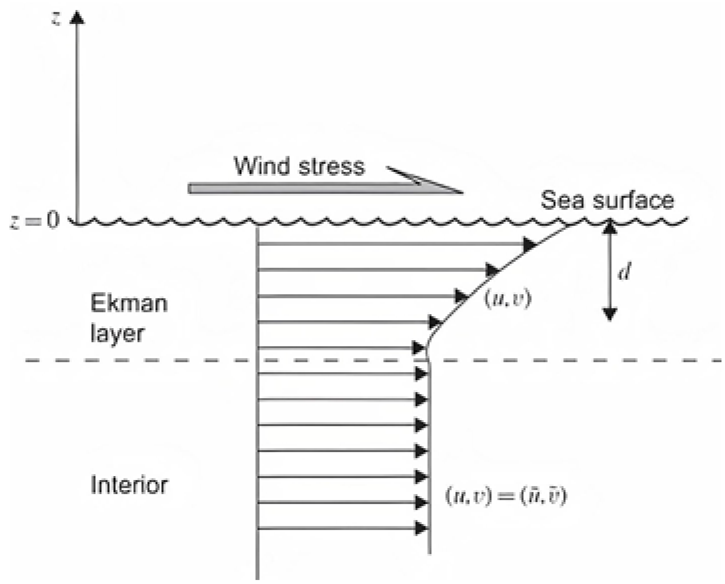

Figure 45. Schematic depicting the influence of wind driven currents against depth in the ocean.

Credit: Cushman-Roisin and Beckers (2011)

Gliders can be commanded to follow a path, but their slow speed can result in aliased data if the field being sampled evolves at a faster rate than it would take the glider to occupy the sample volume. However, gliders can also maintain a geographic location, thereby reducing the impact of their slow speed. This operation is commonly referred to as a “virtual mooring” and allows a glider to hold a station with station-keeping performance similar to that of the surface buoy of a mooring (Rudnick et al. 2004). However, unlike a mooring, a glider can be commanded to move through a satellite communication link to, for example, station-keep at a different geographic location or to move toward shore where it can be recovered. Another advantage over a mooring is that a glider’s vertical motion while holding station allows it to collect data over a continuous range of depths. Because gliders use buoyancy changes for propulsion, holding station does not require significantly more power than any other path-following operation it may perform, thus making the process of station-keeping essentially passive.

Gliders and profiling floats are both heavily influenced by ocean currents because of their slow speeds and limited maneuverability. As a result, networks of these types of UUVs can benefit from using observed ocean currents to conduct more advanced path-planning to improve operational performance. Dahl et al. (2011) investigated path-planning algorithms that used forecasts of strong, time-varying ocean currents to plan missions for profiling floats like those in the Argo array. In their research, they investigated two mission objectives: (1) spatial coverage maximization, dispersion of floats that are deployed from a single geographic location to observe a larger area; and (2) motion toward a specific target location, guiding the floats to a target location for various purposes such as recovery of the UUVs. The efficacy of the path-planning algorithms was tested by running simulations of the float trajectories using ocean current data derived from the Hybrid Coordinate Ocean Model (HYCOM). For comparison, the expected trajectories of floats using the standard Argo control policy (i.e., constant fixed depth at set profiling interval) were also computed. The results of the simulations demonstrated that the algorithms made a substantial improvement in maximizing the spatial coverage of the floats, but made only limited improvement in directing the float toward a specific target location (Figure 46).

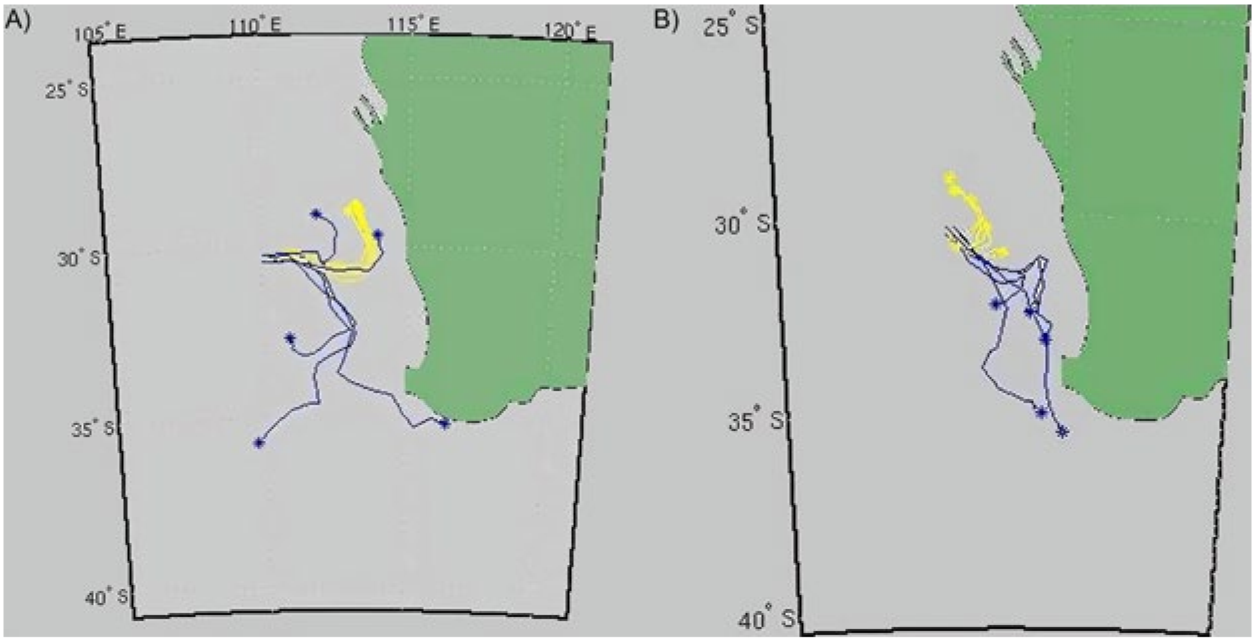

Figure 46. Results of path-planning simulations using models of ocean currents (blue) compared to standard Argo control policy (yellow) for two mission objectives: A) spatial coverage maximization; and B) motion toward a specific target location.

Credit: Dahl et al. 2011

More recent research has also investigated using current-sensitive path-planning of profiling floats for station-keeping. Troesch et al. (2018) investigated using imperfect models of ocean currents in path-planning algorithms for station-keeping of profiling floats. The authors modeled an Electro-Magnetic Autonomous Profiling EXplorer (EM-APEX) vertical profiling float, which is designed to execute more flexible missions than the typical fixed 10-day period of the profiling floats in the Argo array. The EM-APEX also uses electrodes for sensing the electrical currents produced by seawater moving through earth’s magnetic field. allowing it to vertically profile ocean currents, but this capability was not used in the study. After conducting a profile, the EM-APEX reports the data via satellite communications. The satellite communications are also used to update the mission parameters of the float, allowing some ability to control the path of the float. For the simulations conducted, the researchers limited the control to just moving between the surface and the parking depth of the float, staying at the surface, or staying at the parking depth. Every time the float surfaces, a new path is planned for the next profiling cycle. The Regional Ocean Monitoring System (ROMS) was used to model the ocean currents with varying degrees of fidelity. The simulations demonstrated that if the ocean current model used has some degree of validity on its own, the path-planning can be beneficial.

Research on using predictions of time-varying ocean currents has also been conducted to investigate the potential improvements in path-planning for glider UUVs. Thompson et al. (2010) investigated path-planning of gliders that took ocean current forecasts into account, including understanding the impact of discrepancies between forecasts and ocean current measurements. The specific goal of the research conducted was to develop new path-planning algorithms to conduct spatiotemporal missions, where the vehicle reaches a specific location at a specific time. In the research conducted, ocean current forecasts were obtained from the ROMS and simulations with no knowledge, perfect knowledge, and realistic knowledge of ocean currents. The results that Thompson et al. (2010) obtained demonstrated that the path-planning that took ocean currents into account was able to make faster progress toward the target location. Without path-planning some simulations resulted in gliders that were substantially off course, and it was found that one main advantage of the current-sensitive path-planning algorithms was the ability to identify target locations that represented dangerous destinations where the glider would be likely to be pushed off course. Another important finding was that there was no significant difference in performance of the current-sensitive path-planning algorithms that used realistic 48-hour forecasts compared to perfect forecasts.

In addition, novel research efforts have been conducted to station-keep without a significant energy source. Most fish have a sensing system known as a lateral line that allows them to sense unsteady flow and take advantage of it to reduce energy expenditures. Fish will often maintain a position downstream of a bluff body in a zone that exists between the vortices that are shed from the bluff body. When a fish is holding position in one of these zones it will modify its swimming to synchronize to the vortex shedding in a technique known as the "Kármán gait." In research on live fish, it was shown that by using the Kármán gait a fish was able to decrease the tailbeat frequency by 303% compared to swimming in open flow (Liao et al. 2003). Later, Liao (2007) also demonstrated that a dead fish could exhibit motion like the Kármán gait causing it to move upstream, prior to the onset of rigor mortis. This led researchers to believe that the natural resonance of a flexible dead fish behind a bluff body could be responsible for this motion leading. This in turn has led to research to determine if the working principle behind the Kármán gait could be applied to UUVs. Through controlled experiments, Phillips et al. (2016) investigated the feasibility of using a Kármán gait-like motion to allow a UUV to perform passive station-keeping. The study demonstrated that both flexible and rigid cylinders downstream of a bluff body could adopt Kármán gait-like motion that could allow the cylinder to move upstream, although the effect was more pronounced for the flexible cylinder.

In collaboration between the Japan Agency for Marine-Earth Science and Technology and Kyushu University, researchers have prototyped a new UUV that applies a waypoint-holding strategy (Asakawa et al. 2011; 2016; Nakamura et al. 2013). This new vehicle, named Tsukuyomi, typically operates as a glider using buoyancy principles and wings. When at the surface the vehicle will check its location using GPS, allowing it to determine if it needs to change its position, such as if it has drifted away from the desired location for the virtual mooring. Recognizing that profiling floats typically operate for much longer durations than gliders, in part thanks to their ability to “sleep” between profiling events (i.e., freely drifting at their parking depth), the Tsukuyomi is designed to go into a lower power consumption state between measurements to extend its endurance. This can be done in one of two ways: (1) if the water depth is less than the rated maximum the vehicle can gently land on the seafloor, where the lateral flow is minimal (Figure 47); or (2) if the water is deeper than the rated maximum the vehicle can passively drift at a fixed depth below the surface, much like a profiling float.

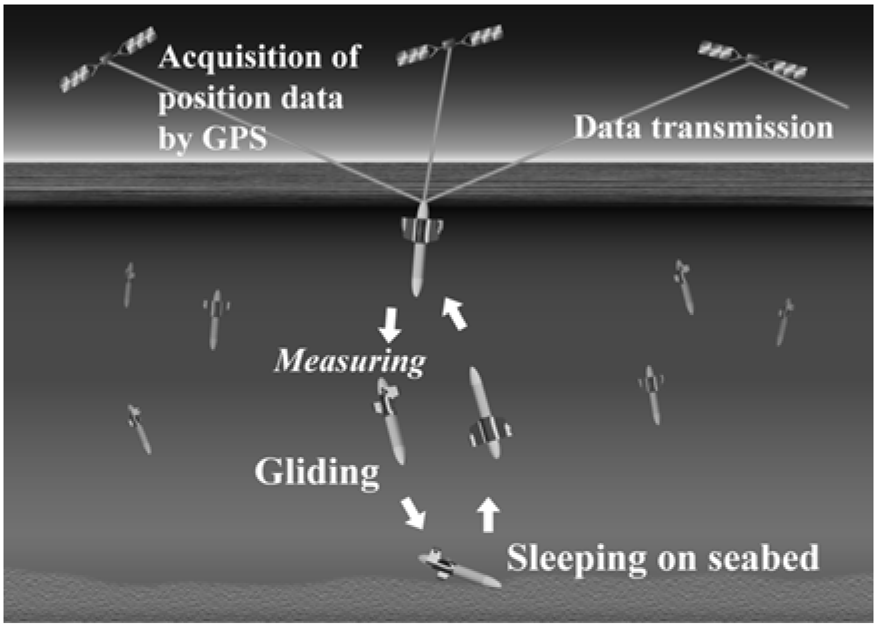

Figure 47. General operations of the Tsukuyomi UUV

Credit: Japan Agency for Marine-Earth Science and Technology and Kyushu University

Another prototype for a hybrid underwater profiling vehicle, that applies a waypoint-holding strategy, was developed by Zhejiang University (Figure 48). The proposed vehicle, named ZJU-HUP, uses an onboard GPS for localization, and when it dives it uses buoyancy to descend vertically, rather than to glide, with any lateral movement primarily being the result of ocean currents. Unlike a profiling float, which would collect profile data while ascending, the ZJU-HUP collects profile data while descending. Once the vehicle reaches the seafloor, it will land and go into a low power state where it will rest while periodically taking measurements from the seafloor. Lastly, after a designated amount of time, the ZJU-HUP will begin to ascend using the previously measured current velocities, which depending on the available instrumentation may either be depth-averaged or a profile, to glide in a way that counteracts drift. Zhou et al. (2020), validated the ZJU-HUP gliding scheme with a numerical model and tested it at sea for its ability to hold a station within a 500 m radius during designated area persistent monitoring. The model results showed that station-keeping is more effective when current velocity profiles are available to correct drift, than when only depth-averaged data currents are known, but this requires additional instrumentation. However, field testing showed that the gliding scheme was effective at remaining within the designated location when only depth-averaged currents were sampled. A comparison of the ZJU-HUP field tests with various other devices in previous literature is presented in Table 5.

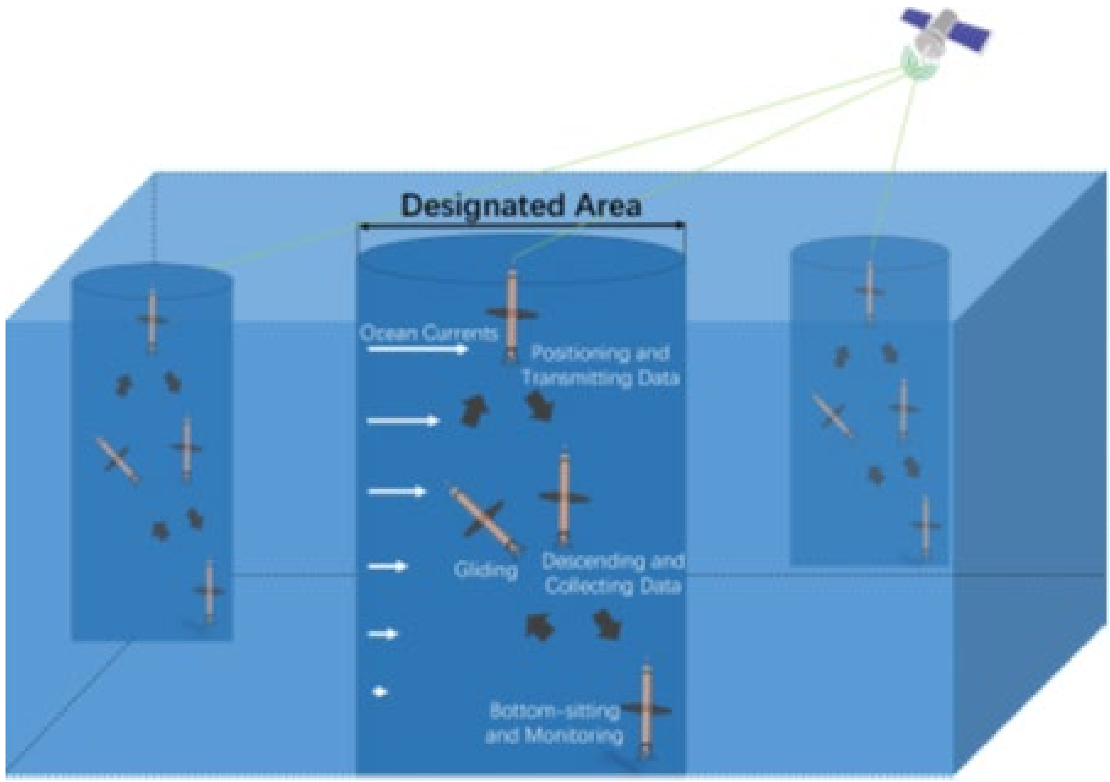

Figure 48. Operation of the hybrid underwater profiler used for designated area persistent monitoring.

Credit: Zhou et al. 2020

Table 5. Comparison of station-keeping performance of different gliders using different approaches

Reproduced from Zhou et al. 2020, Table VI

Approaches	Vehicles	Vehicle speed (m/s)	Current velocity (m/s)	Diving depth (m)	Mission duration	Averaged displacement error (km)	Reference
Basic station-keeping	Slocum	Vertical: 0.2 Forward: 0.45	0.3-0.75	200	10 days	2	Hodges and Fratantoni (2009)
Basic station-keeping	Spray	0.2	0.3	500	14 days 4 days	3.6 1.8	Rudnick, Johnston, and Sherman (2013)
Baseline control using Kalman filter predicted current model	Seaglider	0.25	0.159 (at 15m)	500	14 days	0.692	Branch et al. (2017) and Clark et al. (2020)
Baseline control executing naive box helix dives	Slocum	0.35	0.212 (at 15m)	500	5 days	0.120	Branch et al. (2017) and Clark et al. (2020)
Planner control	Seaglider	0.25	0.141 (at 15m)	500	16 days	0.464	Branch et al. (2017) and Clark et al. (2020)
	Slocum	0.35	0.159 (at 15m)	500	15 days	0.201	
Constant gliding and yaw angle (CGYA)	ZJU-HUP	0.53	0.196 0.186	500	3.33 h 11.01 h	0.384 0.292	Zhou et al. (2020)

5 Synthesis

5.1 Platform comparison

Each of the platforms discussed in this report has distinct advantages and disadvantages, which typically involve a tradeoff between power needs, mission duration, and data types collected (if any). A summary of these tradeoffs is presented in Table 6. Note that except for the first data row, all other entries are based on mooringless platform designs encountered in the literature. TEC platforms were not included in this table as only one conceptual example was found without a mooring system.

Table 6. Tradeoffs for platform advantages. Table ratings are relative to moored buoys (first data row).

Platform	Spatial Coverage	Temporal Coverage	Operating Cost	Capital Cost	Payload Capacity	Expected Station-keeping Ability
Moored buoy	Low	High	Med	Med	High	High
Surface Drifter	Med	Med	Low	Low	Low	Low
USV	High	High	Low	Med	Med	Med
WEC	Med	High	High	High	Med	Low
FOWT	Med	High	High	High	High	High
Profiling Float	High	High	Low	Low	Low	Low
AUV	Med	Low	High	High	Med	Med

5.2 Station-keeping Methods

Following the platform analysis in Section 4, we identified drift mitigation, steering, and propulsion as the principal means of station-keeping. Drift mitigation is a relatively passive way to reduce drift, control heading, and avoid abrupt movements; steering is the action of guiding an object (in this case, a platform or vehicle) in a desired direction, typically via control surfaces; and propulsion is the action of driving or pushing an object forward. Here, we compile the different station-keeping methods encountered in the literature sorted into these categories. Steering and propulsion are discussed in tandem because they are sometimes part of the same subsystem.

5.2.1 Drift Mitigation

Drogues and sea anchors are the most common methods used to control heading and mitigate drift. Sea anchors are designed to stop a vessel and orient it bow-first into the waves, much like a traditional anchor. While sea-anchors will not keep a vessel at a fixed location, they are useful alternatives when the water depth is too deep for traditional anchors. Sea anchors are usually deployed from the bow of vessels in order to orient the vessel into the oncoming waves (Figure 49). Sea anchors can be fashioned from nearly any material that creates added drag; the most common shape is that of a cone or parachute fabricated from a fabric material with vents where water flows from a small opening to a large one. The size of the sea anchor determines the braking power that is applied to the platform.

Figure 49. A parachute sea anchor.

Drogues are used to slow down a vessel or platform and will usually keep a vessel oriented stern-first into the waves. Unlike sea anchors, they are not designed to completely stop a vessel, but to slow the speed, and instead of being deployed from the bow they are generally deployed from the stern. There are two types of drogues: single element and series. A single-element drogue resembles a sea anchor in shape but is typically smaller in size. A series drogue is a series of drag-inducing shapes or objects attached to a common line (see Figure 50). Some drogues can reduce vessel speeds from 30% to 100%, depending on the speed and size of the vessel.

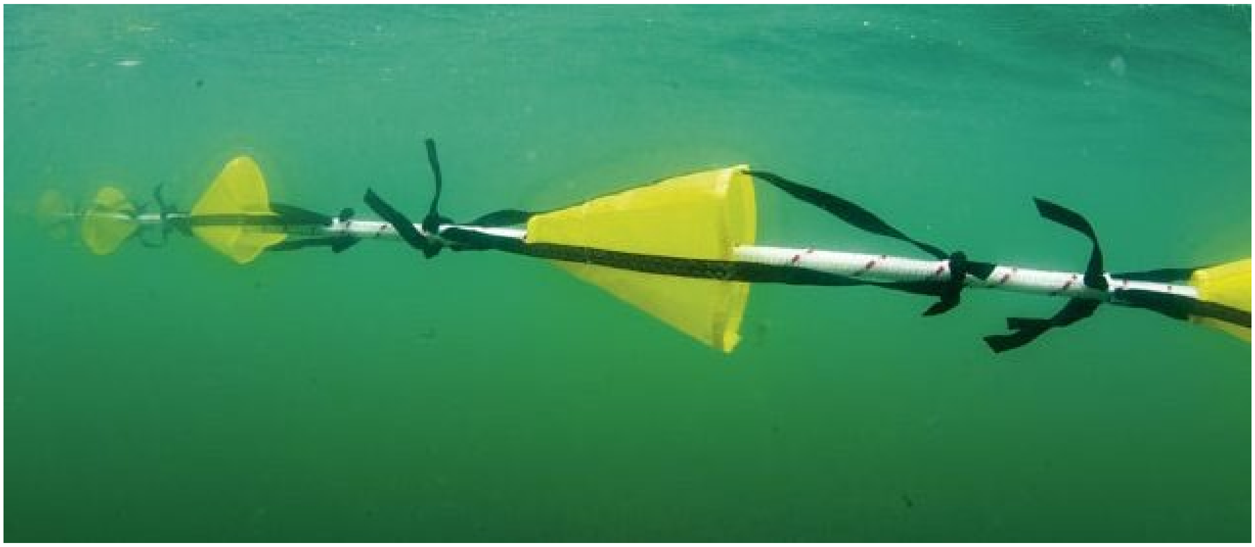

Figure 50. A series drogue.

Surface Drifters

Surface drifters are intended to move with prevailing waves and surface currents and do not have dedicated systems for steering or propulsion by design. Fins and other articulating structures may be used for some control over directional movement, as well as drogues for drift mitigation.

Offshore Renewable Energy Systems

Two of the three mooringless WEC concepts presented in this report use heave-plates that effectively act as drogues and provide drift reduction. All other offshore renewable energy platforms encountered in the literature have steering or propulsion systems and thus will not be mentioned here.

5.2.2 Steering and Propulsion Methods

Methods used for steering that are separate from the propulsion system (if one is present) include the use of control surfaces that react to ocean currents, waves, or winds and provide varying degrees of course adjustments. These control surface areas could be in the form of articulating fin structures (e.g., ship rudder, wing sail, etc.) or static fins that use shifts in buoyancy to cause the platform to roll about its center-of-gravity to initiate a vertical turn. These methods do not generally allow for the very fine-scale navigation and station-keeping that would be required for a platform to stay within a short range to conduct activities such as vehicle recharging.

Other methods used for steering that are incorporated directly into the propulsion system include using differential thrust to simultaneously provide thrust and steering; directional thrusters separate from a primary thruster (or thrusters) that cause the platform to pitch up/down or yaw clockwise/counterclockwise; or a vectored thruster that allows for directing the propulsion in a range of directions relative to the platform's local coordinate system. These methods do allow for fine-scale navigation that could be used for vehicle recharging.

For the platforms and vehicles discussed in this report, propulsion typically requires an energy input, which can be either renewable or nonrenewable. Because the travel speed of path-planning platforms is dependent on the resource, they typically have some form of powered motor.

Buoys and Unoccupied Surface Vehicles

Buoys are generally intended for relatively stationary operations and are typically delivered to their position by another vessel. As such, any steering/propulsion systems on buoys are solely for maintaining station (typically waypoint-holding, as opposed to path-planning). Most unmoored buoys we found use some form of combined steering and propulsion subsystem, mainly differential thrusters, that can be adjusted using control algorithms in fully autonomous modes or be remotely controlled for manual operations. The power for these thrusters can be derived from renewables (solar or wave), electric batteries, nonrenewable fuels (diesel or gasoline), or a combination thereof. The steering and propulsion system designed for the Bunch of Buoys fleet, uses a thrust vector concept, with three pairs of forward and reverse individually controllable motors, and is able to apply both a path-planning and waypoint-holding localization strategy (Zoss et al. 2018). The ENDECO Station Keeping Buoy, on the other hand, while never produced, is conceptualized to use a rotatable airfoil to steer, adjusting direction by reefing and angling the sail (Hanlon 1987).

USVs have the most varied methods for steering and propulsion control, as they are the most mobile of the surface platforms and have significant path-planning applications. This also means that they require the most power. Steering or combined steering and propulsion methods include control of a single outboard motor, paired electric motors or thrusters, waterjet, trim tab and hard wing to catch wind, electric power-controlled rudder, multiple rudders, and more that vary by the manufacturer and model of the device. Most commercial USVs use a propeller either as part of an outboard motor or thrusters, which is most often powered by nonrenewable fuels or a battery. USVs that use renewable energy for propulsion typically harvest the resource and store it in a rechargeable battery before redirecting the energy to control surfaces as needed.

Offshore Renewable Energy Systems

The Halona WEC proposed by Ulm et al. (2020), has protruding wave guides that act as drogues but can be furthermore paired with information of regional oceanic current maps to provide controlled steering.

Of great interest are the sailing-type TEC and FOWT platforms, which use large sail structures to generate lateral lifting forces to propel the VLFS in a switchback motion in combination with a rudder to steer (Terao, Watanabe, and Wakita 2007; Manabe et al. 2008). The semi-submersible platform and large open-ocean concepts presented by Xu et al. (2021) and Alexander (2019) both use energy-intensive thrusters to propel themselves and maintain station and use hydrogen as a form of energy storage to facilitate propulsion.

Unoccupied Underwater Vehicles

UUVs have a limited number of steering methods, and the type of methods typically differ between different sub-categories of UUVs, with AUVs possessing the most varied forms of steering. For AUVs, the steering system could be one or a combination of the following: articulating fins, directional thrusters, or differential thrusters. For gliders, the steering systems are typically either articulating fins or static fins where changes in the center of gravity cause the vehicle to roll about its axis, resulting in a sweeping turn. For profiling floats, though many of these devices do not include traditional forms of steering and tend to drift with the currents, it is possible to plan and predict the roughly defined direction and effect some degree of steering by using models of ocean currents (either depth-average or depth-specific) and depth adjustments to passively navigate.

Another low-energy method of steering involves using models of ocean currents to guide a platform, such as an underwater profiling vehicle, toward an intended location or direction. By using two-way satellite communications, a vehicle's location at the ocean surface, along with profiling or depth-averaged measurements of ocean currents taken each time it submerges, can be used to compute a set of updated operating instructions. These forms of steering are typically used to direct the platform toward a generalized area or to maintain a waypoint with performance comparable to the surface expression of a moored buoy.

UUVs typically use one of two primary methods of propulsion. The first involves using an electric thruster. The thruster is typically powered directly by an onboard battery. The second method involves using a buoyancy engine to generate vertical propulsion by shifting the buoyancy of the device. AUVs typically use an electric thruster while gliders and profiling floats use buoyancy engines. These buoyancy engines pump oil from an internal to external bladder to passively drive propulsion for vertical movement (Roemmich et al. 2019; Rudnick et al. 2004; Hodges and Fratantoni 2009). Control strategies vary (e.g., Troesch et al. 2018; Zhou et al. 2020), and the exact mechanisms have evolved over time, but the power for control typically comes from an onboard electric battery (Gordon 2017). Between gliders and profiling floats, the primary difference for the propulsion system is that a glider can use hydrodynamic fins to convert the vertical motion into horizontal motion, while a profiling float is only able to alter its depth and is otherwise carried by the ocean currents at the specific depth at which it resides.

6 Suggested Further Research

The findings in this report demonstrate that mooringless station-keeping today continues to be a novel concept, and even more so as it pertains to accomplishing this goal using marine renewable resources. Future research should be contingent on identifying significant opportunities to implement specific mooringless technologies that meet demonstrated industry and scientific needs, such as enabling a previously technologically infeasible task or reducing the costs of existing activities, or that create new unforeseen applications altogether. Speculatively, the team has identified the following use cases as potential subjects of interest:

- Mooringless docking for UUV recharging or for georeferencing drifter buoys

  An extended offshore network of docking stations would enable longer and more reliable ocean observation missions in deep ocean regions, as is the intent of the Halona WEC and recharging platform proposed by Ulm et al. (2020). Another solution for this application may be using an autonomous underwater hovering vehicle (Chen, Chen, and Cai 2019).

- Deep-sea floating wind farms

  Deep sea areas of high-wind resource on the U.S. Pacific Coast may become commercially viable using dynamically positioned floating wind turbines as proposed by Xu et al. (2021). Arrays may take advantage of the more efficient space utilization of mooringless systems; in the absence of distancing constraints associated with shared moorings, a higher density of wind turbines may be deployed in a given area of the deep sea (Figure 51).

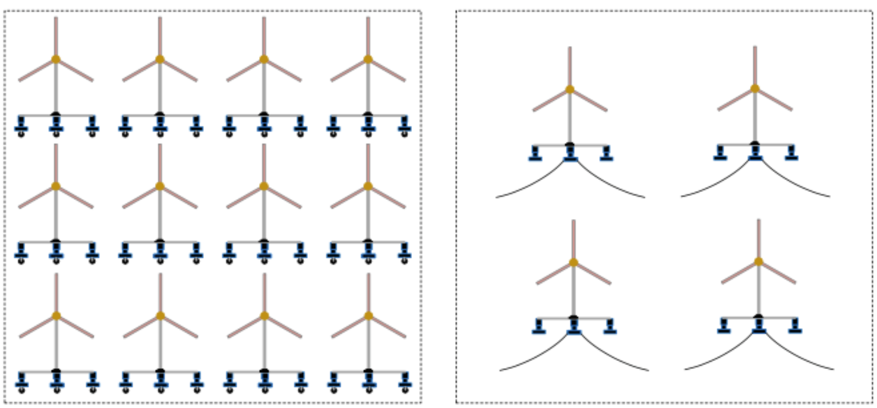

Figure 51. Layouts of a high-density mooringless array (left) and a moored wind farm (right).

Credit: Xu et al. 2021

- U.S. Navy sonar arrays

  The need for persistent, station-keeping sonar arrays to be used by the U.S. Navy in all water depths, and able to provide anti-submarine control of an area for several weeks, is described by Stewart (2017).

- Pacific Ocean wave buoy network

An ocean-wide array of mooringless wave rider buoys may be distributed along the U.S. Pacific Coast, allowing for high-resolution and near real-time monitoring of prevailing wave conditions.

- Pairing hydrodynamic control surfaces with moored systems

  Because mooring line failures are a significant part of the capital costs of moored systems, there may be an opportunity to equip some ocean platforms with control surfaces, such as hydrofoils, to reduce the strain on mooring lines. This is a cross-over with another PBE task team concerned with the resiliency of marine systems and would technically not lead to a *mooringless* application.

Thus, a technoeconomic analysis is first recommended to determine the value proposition of each identified opportunity. Such a study should analyze the technological feasibility and economic value of the proposed opportunity, and the existing costs of current activities, if they exist. For example, the cost of deploying and maintaining a wave measurement buoy array in the Pacific Ocean should be compared to the cost of deploying and maintaining moored buoys. The added benefits of near real-time data availability and broad spatial coverage, which currently have no parallel, may also be quantified. The technoeconomic study may be extended to additional mooringless station-keeping use cases within the PBE space by conducting a series of interviews with scientific and industry contacts to identify new opportunities and collect pertinent data.

In addition, there may be an opportunity to focus further research at specific sites of interest, perhaps identified by other PBE tasks teams, where there are known constraints for moored systems (e.g., depth limitations, sensitive habitats). Also, while numerical models of specific platform station-keeping technologies should follow the suggested technoeconomic study, some generic modeling may be completed sooner to, for instance, model the drift of a multi-device array that could be representative of floating wind farms, mooringless buoys, or WECs alike. Such simulations could be used to estimate the translation of the array given a predefined drift allowance, perhaps borrowing from modeling techniques of plastic drift simulations (Chaturvedi et al. 2020). Later, if a particular mooringless technology is identified for future research, the model could be used to estimate the power requirements to station-keep an array when it is exposed to different sea states.

Currently, most mooringless platforms use nonrenewable energy when they apply a path-planning or waypoint-holding localization strategy. Therefore, it would also be beneficial to conduct a study to assess the power that is specifically allocated/required for station-keeping in systems that use batteries or engines. This would provide more concrete powering targets for alternative systems that use renewable energy. This study would require contacting industry and the scientific community to collect pertinent data and product specifications.

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Appendix A: Bibliography of Preliminary Literature Review

Some of the citations listed below also appear in the References section. They are repeated here to provide a complete list of the 72 sources found in the preliminary literature review discussed in Section 3.

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