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Integrating UUVs for naval applications

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Abstract

Underwater surveillance technology saw its advent in the Cold War. This technology saw numerous advancements only once it was declassified and pursued by the academia. One such advancement in the maritime domain was the development of Unmanned Underwater Vehicles (UUVs), which have the ability to enhance war-fighting capabilities while reducing the risk to human life. Though this technology has since been commercialized, it has found limited uptake by the navy. The limited inroad it has made has been driven primarily by the developers and the governments that fund them. However, since this technology offers numerous benefits to the military, it needs to be integrated into the navy sooner than later. This essentially means that, to achieve greater acceptance for naval use/ applications, integrating this technology into the navy is essential. This, in return, requires numerous queries to be answered and facts to be understood to create greater confidence in the technology and its potential. Accordingly, some of these queries that can help address the knowledge gaps, to facilitate future acceptance and induction of UUV technology into the navy, are discussed. Though an attempt to provide comprehensive answers is made, these answers are not considered complete, but only a starting point for a debate. As it stands, the technology exists; however, it is a lack of imagination that is disallowing its usage.

Acronyms

ALV	Autonomous *Lander* Vehicles
ASW	Anti-Submarine Warfare
ATP	Adenosine Triphosphate
AUV	Autonomous Underwater Vehicle
CN3	Communication and Navigation Network Nodes
CURV	Cable-controlled Undersea Recovery Vehicle
DVL	Doppler Velocity Log
GLSV	Great Lakes Sound and Vibration, Inc.
GPS	Global Positioning System
IUSS	Integrated Underwater Surveillance System
ISR	Intelligence, Surveillance and Reconnaissance
LARS	Launch and Recovery System
LBS	Littoral Battle Space Sensing
LCS	Littoral Combat Ship

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LDUUV	Large Displacement Unmanned Underwater Vehicles
MCM	Mine Counter Measure
MDA	Maritime Domain Awareness
MIT	Massachusetts Institute of Technology
MSR	Marine Scientific Research
MUUV	Medium Unmanned Underwater Vehicle
OEM	Original Equipment Manufacturer
PLAN	Peoples Liberation Army - Navy
PUV	Programmed Underwater Vehicle
REMUS	Remote Environmental Monitoring Units
ROV	Remotely Operated Vehicle
RILS	Reacquire, Identify and Localize Swimmers
SAUV	Solar Autonomous Underwater Vehicle
SOP	Standard Operating Procedures
SOSUS	Sound Surveillance System
SURTASS	Surveillance Towed Array Sensor System
SPURV	Special Purpose Underwater Research Vehicle
SKAT	Also called SCAT- a Russian UUV
TCS	Time Critical Strike
USN	United States Navy
UUV	Unmanned Underwater Vehicle
USV	Unmanned Surface Vehicle
UMV	Unmanned Marine Vehicle
UARS	Unmanned Arctic Research Vehicle
WHOI	Woods Hole Oceanographic Institution
XLUUV	Extra-Large Unmanned Undersea Vehicle

1. Introduction

The military has always been a risky business. Accordingly, efforts to reduce the involved risks to a minimum have been ever-evolving. This has led to the development of new technologies that can enhance war-fighting capabilities while reducing the risk to human life. One such effort is the ‘Unmanned Vehicle’, which has the ability to remove the operator from the platform, making risky and sometimes unrealistic operations possible without the loss of lives. In the maritime domain, Unmanned Marine Vehicles (UMVs) were used during the Second World War, but for limited activities as made feasible by the technology of those times (NAP, 2002, pp. 120-130). After the war, they were researched extensively for greater application by the US Navy through their research funds (NAP, 1996, pp. 7-11). However, meaningful advancements were witnessed only in 1997 after the formation of Bluefin Robotics as a spin-off company of the Massachusetts Institute of Technology Autonomous Underwater Lab (MIT, n.d). Since then, numerous companies (Agarwala, 2020) have mushroomed to convert academic research into commercial technology.

Over the years, as a result of the internet revolution, the development of sub-component technology, and advancements in digitalization, numerous features of UMVs have been demonstrated by academicians, private players, and government developers. While during WWII the application of UMVs was limited to mine clearance and battle damage assessment, today they show promise for use in a wide range of missions of science, bathymetry mapping, military, and environmental surveys (NAP, 2002, p. 122).

For the military, with the maritime threat environment shifting from the ‘blue’ to ‘brown’ waters, the application of UMVs in diverse roles that move away from a conventional to an autonomous one, such as intelligence gathering, surveillance, and reconnaissance, to ensure the upper hand for security forces, is on the rise. In addition, roles such as payload delivery, creating communication and navigation network nodes (CN3), influencing enemy activities by injecting infected/ false information, and base and port security are some other areas where UMVs are likely to be used extensively. An added feature of stealth, along with cost effectiveness, makes them potent platforms for future warfare. It is possible that, in the future, we could witness the collaborative use of UMVs, along the lines of the now defunct US Navy's Integrated Undersea Surveillance System, to monitor large swathes of the oceans and provide superior maritime domain awareness (MDA). It is imperative to mention that these UMVs include unmanned vehicles both *on the surface* and *underwater*, which are usually referred to as Unmanned Surface Vehicles (USV) and Unmanned Underwater Vehicles (UUV), respectively.

The need notwithstanding, due to limited military budgets, the use of UMVs is driven primarily by the developers and the governments that fund their research. However, to be able to fully understand the long-term sustenance and support required for UMVs, certain pertinent questions need to be answered, and facts to be understood, so as to integrate these UMVs into the navy. Since the scope of consideration for both USVs and UUVs is large, the discussion in this article will be limited to that for UUVs. Accordingly, this article addresses some of the aspects of integrating UUVs into the navy. In doing so, the evolution of maritime warfare that led to the development of UUVs is discussed first, followed by discussing some of the numerous questions that need to be answered to assist integration of UUVs for naval applications. The discussion is concluded by analyzing the possible pros and cons of utilizing UUVs in the navy and by recommending some possible checks and balances that can assist in integrating UUVs for Naval application.

It is important to mention here that, while the article aims to provide broad guidelines in decision making, it also aims to initiate a debate to provide clearer thinking for the use of UUVs in a dynamic environment of technology and maritime threat.

2. The evolution of maritime warfare

After WWII, the US Navy realized the importance of using unmanned vessels in risk-based activities. Accordingly, future technological developments of unmanned platforms were undertaken in labs focused more towards UUVs rather than USVs. These specific area studies were driven by the phenomenal increase in the number of submarines held by the Soviet Union during the Cold War. As a result, the Integrated Undersea Surveillance System (IUSS), consisting of the fixed Sound Surveillance System (SOSUS) and the mobile Surveillance Towed Array Sensor System (SURTASS), was put in place by the US. Given the sensitive nature of the equipment, the existence of the IUSS remained classified until the end of the Cold War. Eventually, when in 1991 the system was declassified and made available for research, resource management, and education, so as to study the seafloor data and predict events such as natural calamities, track migrating whales, and detect illegal driftnet fishing on the high seas, it saw numerous technological advancements. These advances allowed the technology to be commercialized and to be made easily available, thereby bringing the mysteries of the underwater realm of the oceans closer to the commoner. In addition, such easy accessibility increased the demand for security from threats emanating from, and under, the ocean. It is no wonder that the 'unmanned underwater vehicle (UUV)' field began to catch the fancy and attention of many maritime nations (Sunak, 2017; Asia Times Staff, 2017; Chalfant & Beavers, 2018; Abramowicz, 2018; Stephan, 2018).

3. Developments of UUVs

Looking back in time, one realizes that there is scattered information with regard to the development of UUVs, with very little effort having been made to consolidate this information (He et al., 2020). Before we proceed to discuss the development of Unmanned Underwater Vehicles (UUVs), it is essential to understand that the term UUV is a generic one that refers to submersibles that can operate underwater without an occupant. These submersibles may be partly autonomous, hence requiring a tether, or be fully autonomous, hence without a tether, and are referred to as Remotely Operated Underwater Vehicles (ROVs) or Autonomous Underwater Vehicles (AUVs), respectively.

Though the exact history of the construction of the first UUV is not clear, the initial credit for developing underwater robots is given to Dimitri Rebikoff's efforts in 1953 and the Programmed Underwater Vehicle (PUV) of the US (Sea Technology, 2019). In the 1960s, robots controlled by the use of cables (called CURV- Cable-Controlled Undersea Recovery Vehicle) were used to recover underwater ordnance of the WWII era[†] and, by the 1970s, they were mostly used for gathering and transferring underwater data. It was, however, only in the 1970s and 1980s that experimental and theoretical growth of ROVs took place, as a result of the oil boom, with the field trials being conducted in the 1980 and 1990s. This period saw the development of numerous designs of ROVs that helped replace divers for underwater work. The period of 1990-2000 that followed saw the development of 'goal fulfilling technologies' that aimed at ensuring the completion of designed goals in an allocated time, thereby encouraging their commercialization. Once ROVs moved to the commercial sector, faster development and the use of innovative materials was seen from 2000 to 2010. However, they remained unaffordable and, hence, unpopular.

While ROVs were being developed, so were AUVs. The first AUV was developed in 1957 at the Applied Physics Laboratory, University of Washington (two versions were developed, viz. SPURV- Special Purpose Underwater Research Vehicle and UARS- Unmanned Arctic Research Vehicle), followed by design refinements by the Massachusetts Institute of Technology (MIT) in 1970. At nearly the same time, the scientists of the Academy of Science, USSR, developed the SKAT (also called SCAT) in 1974. These were followed by the ARCS, by the Canadian Hydrographic Service in 1983, SAUV (Solar AUV) in 1988, and REMUS (Remote Environmental Monitoring Units) in 2001 (Gafurov & Klochkov, 2015; Zhilenkov, 2016), and many more in the years to follow. Over these years, 243 unique configurations of 139 vehicle platforms of AUVs alone were developed in different sizes and configurations (AUVAC, n.d), operating at different depths. To date, the maximum designed depth of AUVs is 6,000 meters, primarily because the gravity anomaly at deeper depths requires manual intervention to account for the environmental changes in real time, as automated calculations can be tricky and erroneous (Jiang et al., 2019). This design is based on shallow water conditions (Humphris, 2009), with the buoyancy balance achieved with standard atmospheric pressure, followed by a step by-step trial to determine the ballast required for greater depths (McPhail, 2009). Multiple trials for depths greater than 6,000 meters can be challenging due to the harsh environment at greater depths and technical, funding, and voyage limitations. This said, true AUVs, such as the Vityaz-D (Russia in May 2020) and the Haidou-1 (China in June 2020), and hybrid unmanned autonomous vehicles (consisting of both ROV and AUV modes), such as the Nereius (Woods Hole Oceanographic Institution) and the Haidou (China), have been developed and proven to be effective at the maximum available ocean depth of 10,908 m, as seen in **Figure 1**.

[†] CURV was designed to recover test ordnance from depths of 600 m. It achieved fame in 1966 when it recovered a Hydrogen bomb off the coast of Spain.

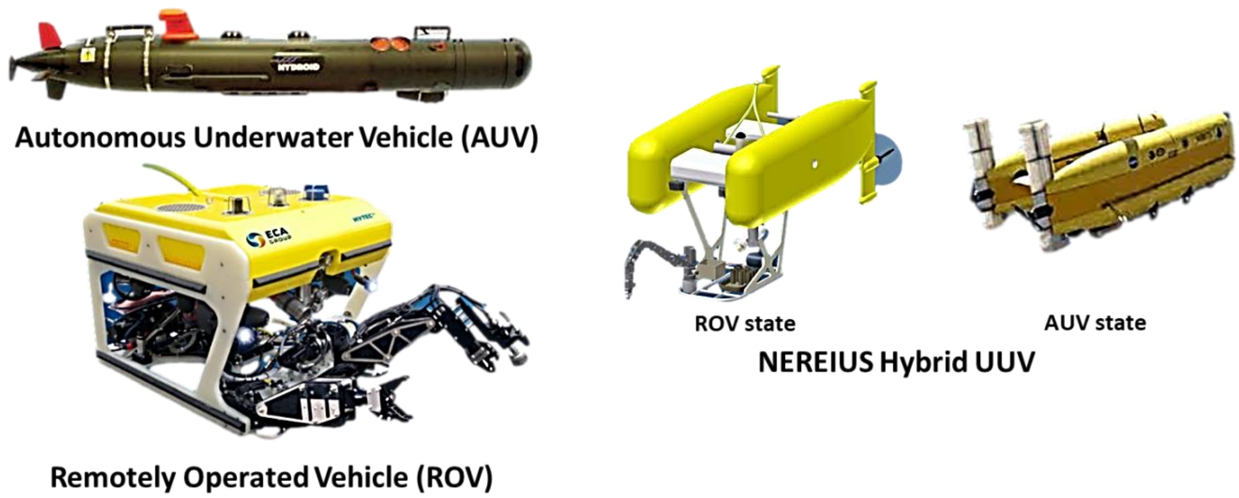


Figure 1 Broad types of Unmanned Underwater Vehicles.
Source: Author's compilation, from various sources.

From 2010 onwards, the development of cooperative control technology has allowed the use of AUVs in groups/ swarms to improve the accuracy of data collected. This has led to reassessing their utility and to identifying numerous roles for them, as seen in **Figure 2**. While numerous advances have been made in the development of UUVs that has increased their possible roles, much more needs to be done to achieve autonomy. Today, research continues to further these advancements in various aspects of design (Shankar & Vijaykumar, 2020; Guggilla & Vijaykumar, 2021), maneuverability (Rayaprolu & Rajagopalan, 2019; Shankar & Vijaykumar, 2021), hydrodynamics (Guggilla & Vijaykumar, 2018, Guggilla & Vijaykumar, 2019a, Guggilla & Vijaykumar, 2020a, Guggilla & Vijaykumar, 2020b), mooring (Guggilla & Vijaykumar, 2019b), and numerous other areas that would help improve the functionality of UUVs.

When looking at naval roles, the interest of UUVs for naval applications was re-kindled when the US released its UUV Master Plan in 2004 (DoD, 2004). Since then, the use of UUVs for military activities has been defined and refined a number of times, owing to changing threats and ever-evolving technology. This allowed shortlisting their possible role into broad areas that include (a) information gathering through Intelligence, Surveillance, and Reconnaissance (ISR)[‡] and establishing Communication and Navigation Network Nodes (CN3), (b) underwater warfare by searching, classifying, mapping, reacquiring, and identification of marine mines and against submarines by undertaking hold-at-risk mission to monitor submarines that enter/exit a given area, (c) Inspection and Identification of underwater assets, (d) physical, bathymetric, acoustic, and bioluminescent mapping of the ocean for operations and countermeasures, (e) payload delivery of frogmen and/or explosives, and Information Operations (IO) by injecting fake/infected information, (f) Time Critical Strike (TCS)[§] (NAP, 2002) to ensure accurate and adequate strike on a designated target when required, and (g) barrier patrol to ensure power projection and force protection and for expeditionary operations and sea base support, as seen in **Figure 2**. While the requirements are well laid out, their actual use is limited by issues of underwater communication, data transfers, and

[‡] ISR is an effort to acquire, process, and provide accurate, relevant, and timely information and intelligence to assist improved decision making against enemy threats, so as to enhance military effectiveness. It is performed for all domains to ensure success of operations. The information may be acquired using satellites, aircrafts, specialized equipment, and/or human teams.
[§] TCS aims to reduce the execution time required to detect, decide, engage, and assess Time-Critical Targets (TCTs) that have a limited window of vulnerability towards detection and destruction.

latency (Yannick & Shahbazian, 2014, p. 41) and, hence, it is mostly a guarded secret by countries that are developing and experimenting with military prototypes.

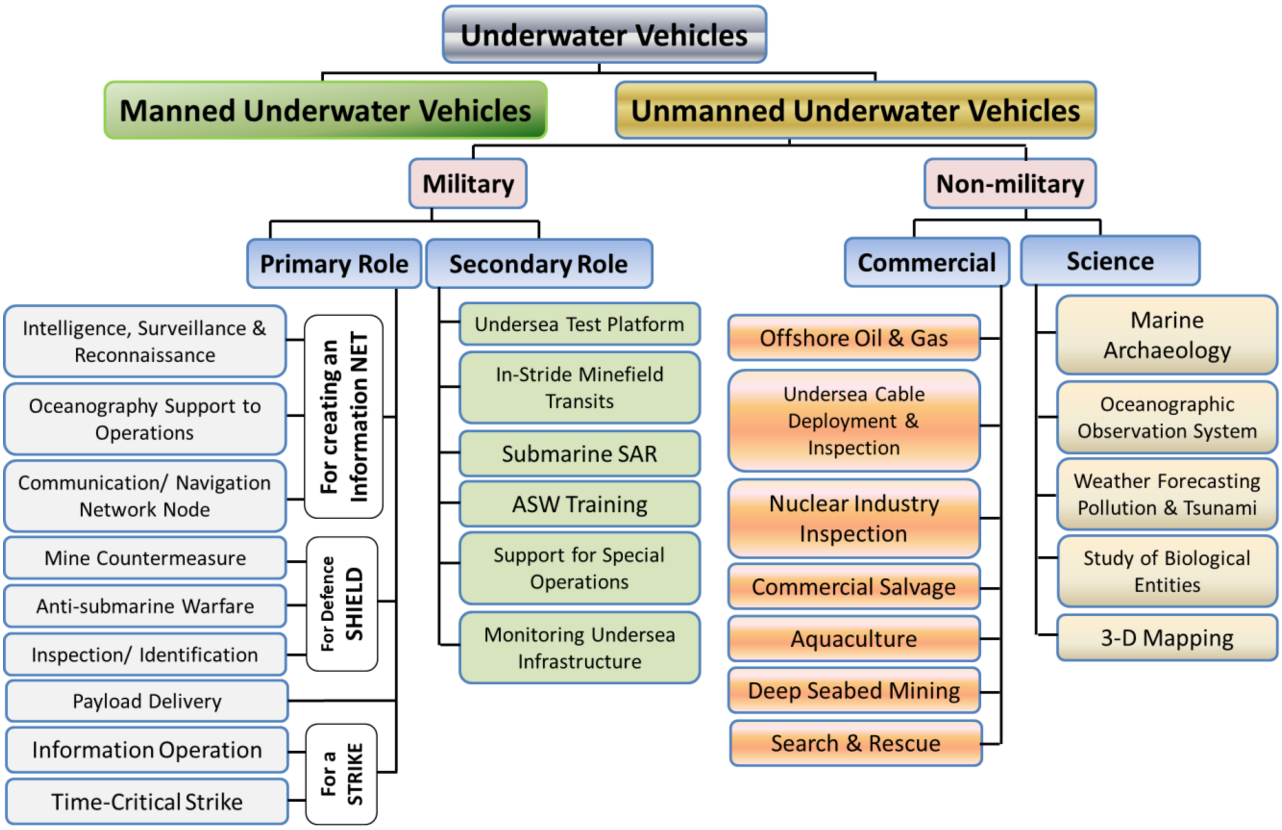


Figure 2 Role of UUVs.
Source: Author.

Like commercial UUVs, military UUVs too may be partly or fully autonomous. When fully autonomous, they undertake pre-defined activities with no intelligence of their own, as the activity to be undertaken is programmed into them. While this programmed information may make them appear intelligent, they are actually not so, since the actions and decisions taken by them are pre-defined. To make them actually intelligent and, hence, increase their utility, they need to be made more adaptive and provided with their own intelligence through the use of AI, an effort currently being pursued by China (Chase et al., 2015). On the other hand, partly autonomous UUVs have an important relevance for naval applications and can be utilized effectively to suit dangerous requirements and conditions on ground. This said, it is important to mention that UUV operations are not entirely binary, as discussed above, but have various levels of autonomy as seen in **Table 1**.

Table 1 Levels of autonomy for an underwater vehicle.
Source: Author's compilation, from various sources.

Level of autonomy	Features
No autonomy	Entirely tele-operated.
Robot assistance	Some automated functionality provided, e.g., maintaining depth with control with the operator.
Task autonomy	Executes motions under guidance, e.g., travel between two pre-defined points.
Conditional autonomy	Human selects the options recommended by the UUV.
High autonomy	The UUV plans and executes the mission on broad Boundary Conditions specified by the user. No control with the operator.
Full autonomy	Requires no human input. Deployed in the environment independently.

Since UUVs are small in size, they can operate in shallow depths and constrained waters, thereby assisting in collecting data for oceanic spaces that were earlier difficult to map in real-time, especially from the point of view of underwater threats. This feature, along with their prolonged endurance at sea, makes them an attractive option for Intelligence, Surveillance, and Reconnaissance (ISR). In addition, their ability to 'hold at risk' in an ASW mission can prevent submarines to leave or enter harbors, while allowing them to trail and destroy submarines if required.

It is essential to understand that the initial advancement of UUVs was driven by the commercial needs of the oil and gas industry, which included underwater surveying, pipeline inspection, and monitoring, and yielded a number of reliable and relatively mature systems which were primarily based on simple and predefined requirements. However, for military roles, where requirements are more dynamic, their usage has only become possible now, as the enabling technologies have advanced sufficiently to support the envisaged areas of application (Evans, 2010). However, what remains to be debated and discussed is how UUVs can be seamlessly integrated for naval applications.

4. Classification of UUVs

Before we delve into the questions to debate the use of UUVs and their possible integration into the navy, we need to understand the basic classification of UUVs, keeping in mind that 'UUV' is a generic term that encompasses all underwater vehicles that can be operated without a human occupant. At the risk of repetition, it is important to reiterate that these UUVs can be either fully autonomous or partly autonomous. While the definition is explicit, some discussions still tend to use the term AUV (an autonomous UUV) interchangeably with UUV. Though this is not entirely incorrect, one needs to remember that an AUV is only a special type of UUV.

When classifying UUVs, they can be done so based on weight, length, propulsion, endurance, or operation. The US Navy UUV Master Plan of 2004 (DoD, 2004) divides the UUVs into four classes, based on weight and endurance, as seen in **Table 2**. One notices that, as length increases, the endurance of a UUV increases too. Similarly, their classification, as per propulsion, can be seen in **Table 3**, by operation in **Table 4**, and by length in **Figure 2**. Though the different types of classification have been enumerated, it is important to understand that, at times, there is an overlap in these defined classifications, and one type of UUV may fall in multiple classes.

Table 2 Classification of UUVs by weight.
Source: Author’s compilation, from various sources.

Serial Number	Type	Weight (kg)	Endurance Low hotel load (hrs)	Endurance High hotel load (hrs)	Diameter (cms)	Launched from	Example
(a)	Small UUV or man-portable vehicle class	11 – 45	10 - 20	< 10	> 7.5 and < 25	Small water craft manually	Mk 18 Mod 1 (Swordfish), IVER, Sandshark, REMUS 100
	Mini-AUV	20 – 100					RoboPike, Robo-lobster
	Micro-AUV	< 20			21.5		Robo-fish
(b)	Medium UUV or Lightweight vehicle class	225	20 - 40	10 - 20	> 25 and < 53	RHIB using launch-retriever system or cranes from surface ships	Mk 18 Mod 2 (Kingfish), LBS-AUV, LBS-G, Knifefish, LBS-AUV(S) Razorback
(c)	Large UUV or Heavyweight vehicle class	1,350	40 - 80	20 - 50	> 53 and < 210	Submarines or surface ships	Snakehead Ph1 Vehicle, Snakehead Inc. 1
(d)	Extra Large UUV or Large vehicle class	10,150	>> 400	100 - 300	> 210	Surface ships or pier	LDUUV, XLUUV, ORCA

Table 3 Classification of UUVs by propulsion.
Source: Author’s compilation, from various sources.

Serial Number	Propulsion	Types of UUVs	Examples
(a)	Screw propulsion	Use a conventional screw propulsion	ROVs, AUvs
(b)	Buoyancy driven	Use change in buoyancy and trim by using a pump and use aerofoil to convert up-and-down motion to forward motion.	Gliders, Seaglider, Deepglider, SLOCUM-Electric, SLOCUM-thermal, XRAY

Table 4 Classification of UUVs as per their operation.
Source: Author’s compilation, from various sources.

Serial Number	Type	Explanation	Examples
(a)	Towed	Act as platforms for various sensor suites attached to the vehicle frame.	Towed array sonar
(b)	Tethered	Are connected to the mother ship for power and operation by an operator on the mother ship.	ROV
(c)	Untethered	Are not connected to the mother ship. Contain power onboard, and may be controlled by a remote operator via a communications link or pre-programmed.	AUV, Glider
(d)	Landers	Are autonomous, consisting of a metallic frame with instruments that land on the ocean floor to measure physical properties along with time-lapse images.	ALV
(e)	Crawlers	Are autonomous, mimic creatures of the sea, and crawl on the ocean floor.	Robotic fishes, crabs, snakes, or octopus

5. Use of UUVs in the navy

In order to integrate UUVs for naval applications, it is essential to understand the possible areas of application and the possible missions UUVs can undertake. Such an understanding will help strengthen the range of utilization of UUVs and help the user to make a better and more informed decision.

5.1 Mission profile

While the broad roles in which UUVs can be utilized by the military have been spelled out in **Figure 2**, herein, we will discuss the possible mission profile for each of these roles (DoD, 2004; Ray et al., 2011). To date, countries like the US (DoD, 2004), Russia (Allik et al., 2021), and China (Chase et al., 2015) are known to operate numerous military UUVs of various sizes and shapes. Some select ranges of military UUVs of the US are seen in **Figure 3**, while some select military LDUUVs of other countries are shown in **Figure 4**.

(a) *Intelligence, Surveillance, and Reconnaissance*. Collecting critical electromagnetic and electro-optic data from the ocean would assist in extending information on denied areas, especially shallow waters that are otherwise inaccessible to conventional platforms. Such areas can be accessed easily by UUVs to provide the desired information.

(b) *Oceanography*. To achieve higher degrees of operability in extreme ocean environments, it is essential that real-time intelligence data is collected and made available to the operators for better planning during an offensive situation. Since collecting such data is limited from manned platforms due to 'user comfort and safety' considerations, unmanned and fixed platforms are considered a possible way ahead (Agarwala, 2020).

(c) *Communication / Navigation Network Node (CN3)*. By providing a closed loop network between manned and unmanned platforms, CN3 systems help provide greater connectivity and control of underwater platforms which otherwise have to surface in order to refresh their GPS for navigation. Such a communication network allows greater safety and control for UUVs while helping them to be used for ISR activities with ease and for prolonged durations without detection (Munafò & Ferri, 2017).

(d) *Mine Countermeasures*. To ensure that harbors and channels are safe for operating warships, and to ensure that similar harbors and channels of the enemy are unusable, the simplest form of offensive is to lay 'sea mines'. In order to do so without risking human life, UUVs are employed effectively. By using UUVs from any platform, the effectiveness to lay mines in enemy waters and clear mines in own waters increases and obviates the need to rely on specialized Mine Sweepers.

(e) *Anti-Submarine Warfare*. In order to 'hold at risk' submarines operating in confined waters, choke points, or in the vicinity of a fleet, UUVs can be highly effective. In doing so, they can provide the requisite safety to the manned platform, while limiting the operation of enemy submarines.

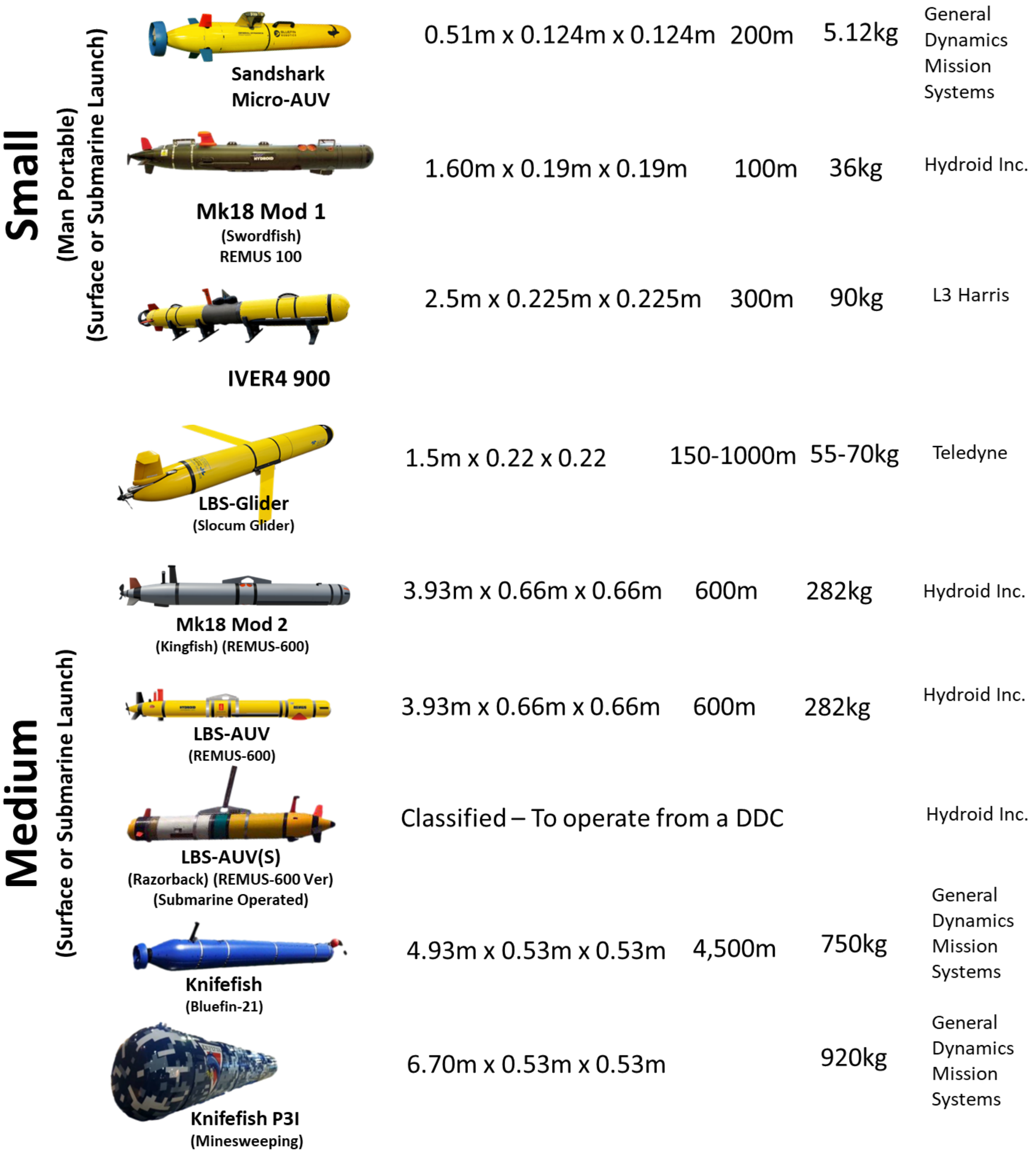
(f) *Inspection / Identification*. In order to perform a rapid search of confined spaces in ship hulls, in and around piers, and berthing areas to rule out anti-terrorism concerns and ensure explosive disposal, if required, UUVs can be used extensively and effectively. Such efforts would ensure safe harbors, waterways, and berths.

(g) *Payload Delivery*. Since UUVs are hard to detect and can operate in shallow waters with ease, they can be used to deliver payload clandestinely. This payload may be in the form of supplies behind enemy lines of ordnance for destroying enemy assets.

(h) *Information Operations*. Due to their small size and their ability to function with ease in shallow waters, UUVs are potent platforms to be used for information gathering. In addition, they can be used as decoys and as communication network jammers.

(j) *Time Critical Strike*. To be able to deliver ordnance with time precision and by minimizing the reaction time of the enemy is a critical activity. When ordnance is delivered by

UUVs, it can be delivered closer to the shore, ensuring lesser reaction time to the enemy. Such an act also helps avoid revealing the position of larger manned platforms against a retaliatory strike.



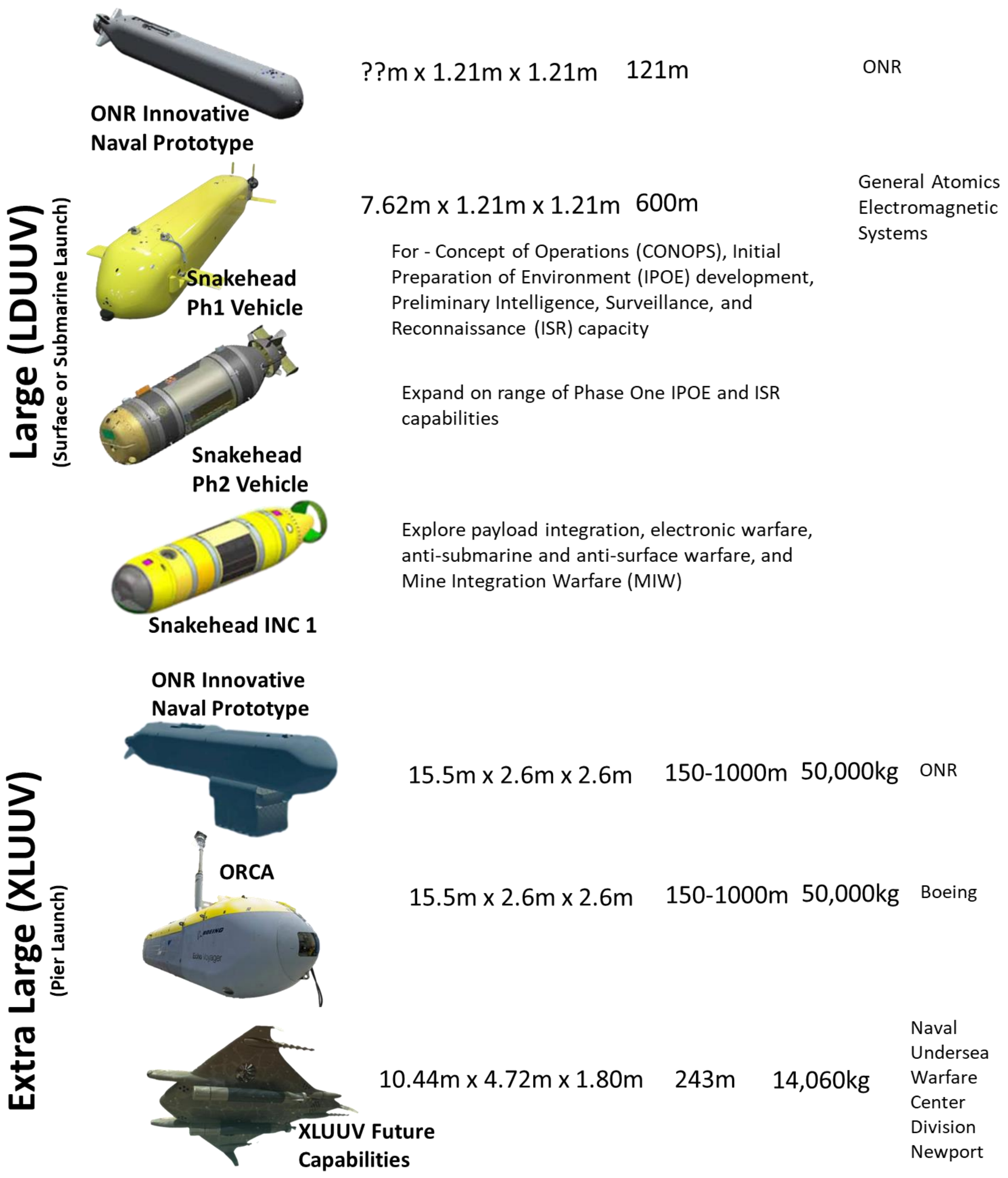


Figure 3 Range of military UUVs of the US.
Source: Author’s compilation, from various sources.

Figure 4 Selected military UUVs of nations other than the US.
Source: Author's compilation, after Sutton, 2019.

5.2 Sensors and equipment onboard

Due to the wide spectrum of use for UUVs, there are a large number of sensors that are used by them. Typically, these may include compasses, sensors (depth and biological to measure turbidity, pH, dissolved oxygen, chlorophyll, etc.), sonars, magnetometers, thermistors, and conductivity probes (Neira et al, 2021). In order to simplify understanding, these sensors may be divided into three broad groups.

(a) Navigation sensors (to sense motion of the vehicle) that consist of gyroscopes and accelerometers, supported by three-axis velocity input from Doppler Velocity Log (DVL).

(b) Mission sensors (to sense the operating environment) to measure numerous oceanographic variables such as temperature, pressure, nitrate, conductivity, and total ATP (adenosine triphosphate).

(c) Proprioceptive sensors (to provide the vehicle diagnostics) such as optic sensors (video cameras), engines and thrusters, luminaries (for providing light), and manipulators.

While navigation and proprioceptive sensors are common to commercial, military, and academic vehicles, mission sensors are specific to the planned mission of the vehicle. At times, many sensors cannot be fitted when the desired endurance is high. The number of sensors that can be utilized is directly dependent on power consumption, size, and their impact on the stability of the platform. It has been observed that using biological and biogeochemical sensors have posed the greatest difficulty (Whitt et al., 2020). In order to improve performance of the vehicle without compromising on the data collected, interoperability of sensors is considered a possible way ahead.

5.3 Stealth parameters

With improvement in sensor technologies, the concept of 'stealth' has begun to encompass avoidance of radar radiations and noise and vibration signatures generated by the vehicle, while ensuring the minimum generation of heat. Accordingly, studies are focused towards the following areas (Gerigk, 2016).

(a) Size and vehicle hull form.
(b) Hull-form resistance.
(c) Minimizing noise, vibrations, and heat factors and their impacts.
(d) Minimizing electromagnetic and acoustic signals produced.
(e) Avoiding and absorbing electromagnetic and acoustic signals incident on the vehicle.
(f) Minimizing visibility.

5.4 Limitations

Even though the technology associated with the development and use of UUVs has advanced many folds since the first prototype was developed in 1953, research and development continues to address various technological limitations of UUVs. While some known limitations are discussed here, there are many more that are unknown and lurking round the corner that would surface with future advances in technology.

5.4.1 Autonomy

In order to ensure seamless and independent operations while ensuring stealth, it is essential that autonomy and control is achieved to precision and high standards. Accordingly, research continues in this field for commercial, military, and academic UUVs. This requires the platform to differentiate between hostile and benign environments and abort or alter missions if events/data collected is unanticipated. The need for higher autonomy is compounded by the inability to communicate real-time with the UUV while underwater and, hence, is a limitation for which research is ongoing.

5.4.2 Energy

In order to achieve higher endurance, continuous power is required by the UUV and, hence, is an area of research. The need to optimize between size, payload, cost, signature, speed, and endurance makes the entire research complicated. While research continues in air-independent technology, fuel cells, and hybrid systems, limitations in available technology further compound the effort.

5.4.3 Sensors and sensor processing

Sensors and their effectiveness play a major role in the success and effectiveness of the UUV in accomplishing the assigned task. Though acoustic sensors are presently the ones being utilized, research into non-acoustic sensors would help improve their effectiveness. Another area of interest is the ability to process, make decisions, and implement retaliatory actions based on the input received from the sensors. While underwater navigation without surfacing to refresh the GPS is an issue, alternatives such as CN3 and terrain mapping have been tried out with some success and are being explored extensively.

5.4.4 Communications and networking

Communicating with the UUV without exposing the communication to interceptors is an essential requirement for successful ISR activity. It is important that the bandwidth to be used and the range of communication to be achieved are studied, analyzed, and developed along with the necessary infrastructure to support the UUV. The requirement becomes challenging when the number of vehicles operating in tandem increases, as in 'swarm' operations.

5.4.5 Engagement / Intervention

Since UUVs operate in littoral waters where the density of fishing nets is high, mechanisms and procedures need to be developed to ensure the operation of UUVs in these waters, while ensuring that entangled UUVs can be retrieved. For this, research is required in areas that address detecting fishing nets and avoiding them or cutting them when detected.

5.4.6 Data transfer

Retrieving collected data from the AUV is an essential task. However, if the AUV has to return to base to transfer data, the range of operations and time on task can be seriously hampered. Accordingly, processes such as data transfer through satellite link, underwater docking stations, and working in swarms are being experimented with (Agarwala, 2020).

5.4.7 Change of roles

Since the mission profile for UUVs is large, possessing a fleet of each variant and having all variants available at every location of operation may not be feasible. It is, thus, essential that modular construction of UUVs may be resorted to, so as to increase their versatility by merely changing a module to achieve changes in roles.

5.4.8 Launch and recovery

The size of the launch and recovery system for a UUV is related directly to the size of the UUV and the sea state in which the launch and recovery needs to be executed. Due to the deck size required for these operations, the operation of UUVs from warships may be difficult, especially if larger UUVs are utilized. Conversely, auxiliaries from where they can operate may not operate close to enemy coastlines. It thus becomes essential that the possibility of using smaller and lighter UUVs from frontline warships be studied and evaluated to achieve greater impact.

5.4.9 Certification of ships

Ships from where UUVs are launched need to be limited in their shock and deck strength characteristics and volume requirements. Such changes may impact the functionality of the existing equipment on these ships, thereby requiring an optimized balance and, hence, greater study between the primary requirement of the ships and the utilization of the UUVs.

5.4.10 Simulation and visualization

In order to evaluate UUVs at the design stage, defining a mission, the environment of operation, and the safety regime required needs to be done for the proposed utilization. This needs to be done after due consideration to ensure optimal results. However, achieving them practically may be a challenge. Shortfalls, if any, need to be considered and, if required, suitably extrapolated, if essential, during the final evaluation of the UUV.

5.4.11 Interoperability and connectivity

Since the use of UUVs in the military is required for a wide spectrum of activities, the same needs to be incorporated during the design stages to ensure the availability of operating systems that function through established communication procedures and which are effective in hostile environments.

6. Integrating unmanned technology into the navy

It is an accepted fact that navies have always been technology centric when compared to the other fighting arms. This said, it is also an accepted fact that the maritime industry, by and large, has lagged behind in adopting new technologies. This is primarily because the industry is averse to risks and is driven primarily by pressure from regulators, commercial requirements, the obsolescence of existing technologies, and/or the inability to cope up with increasing demands at sea and/or in harbor (Agarwala, 2021a).

Integrating UUVs into the navy also has similar concerns. While the technology is commercially available, and the sensors have advanced to an extent that can fulfil the needs of the navy, there are numerous questions that need to be answered or debated before UUVs can be integrated for naval applications of any magnitude. Even though we may discuss, debate, and maybe resolve these issues, the selection of the UUV to be used has to be undertaken independently based on the desired technical requirements. These requirements notwithstanding, let us debate each of the questions, in no particular order of preference or precedence, and try to answer them to develop clarity of how UUVs can be integrated for naval applications.

6.1 Why do we require UUVs?

With the development of nuclear submarines, the oceans have become a space where submarines can be easily concealed. To add to this, ocean sensor technology is developing at lightning speed, and countries are using information collected through Marine Scientific Research (MSR) for military purposes (Agarwala, 2021b). There are also reports in which the UUVs of a country have indisputably been found on the shores of other countries with the intention of intelligence gathering (Darmawan, 2021). Countries like India have also seen terrorism from the sea, which may be attributed to a certain lack of maritime domain awareness.

These all, in effect, point to a dire requirement of investing in UUVs for surveillance and intelligence gathering in own waters in a defensive role, and in foreign waters to protect own assets in hostile areas, as experienced by the USN in Iranian waters during early July 2012. By using small semi-autonomous ROVs, called ‘SeaFox’, the USN was able to locate and destroy mines remotely within minutes of deployment. Even earlier, the USN used REMUS UUV in 2003 to locate mines in the sea lanes to the port of Umm Qasr (MSC Conference, 2012).

6.2 From where can they be sourced?

A good summary of UUVs that can be utilized by the military has been made by Button et al. (2009) and Hardy and Barlow (2008). Today, over 178 UUV platforms (RAND, 2019) exist after design efforts of over 50 years. However, only a few of them are sold, and only by a select few companies. There are around 10 companies worldwide that sell AUVs in the international market. These include Kongsberg Maritime, Hydroid (now a wholly owned subsidiary of Kongsberg Maritime), Bluefin Robotics, Teledyne Gavia (previously known as Hafmynd), International Submarine Engineering (ISE) Ltd, Atlas Elektronik, and OceanScan. When looking at UUVs, we find that the top companies operating in the field of UUVs include Kongsberg Gruppen (Norway), Teledyne Technologies Inc. (US), Lockheed Martin Corporation (US), Saab AB (Sweden), L3 Technologies Inc. (US), SubSea 7, Atlas Elektronik GmbH, International Submarine Engineering Ltd. (Canada), ECA Group (France), and Gabri S.R.L (Italy) (Research and Markets, 2018). Of these, Saab Seaeye and iRobot design, manufacture, and sell their vehicles directly with the help of scientific research networks, while most of the other companies are integrators of sub-components produced by sub-vendors (IndustryArc, 2018). One can note that, today, the US is the largest developer, manufacturer, operator, and supplier of UUVs across the world, with the major manufacturers based in North America and Europe. However, market reports indicate that new growth opportunities are emerging in countries like China, Japan, India, Saudi Arabia, and the UAE for UUVs (Research and Markets, 2018).

6.3 Is the technology fully developed?

The technology is not fully developed and is evolving on a daily basis. It is important to mention that there are numerous variants of UUVs. A study by RAND in 2019 identified nearly 178 UUV platforms (RAND, 2019), of which nearly 145 types were AUVs (Hunt, 2013). All of them are in different stages of development and use. Indulging in all of them may not be appropriate or required. There are, however, some platforms that have been proven at sea by the US, such as the Knifefish (an MCM UUV). The selection of a platform should be based on the task to be performed, for which a number of alternatives would be available. Selecting the right one based on track record and cost would be the key to selecting the type of UUV to be utilized by the navy. Knowing that these vehicles face numerous limitations should not dissuade their use, as most of the limitations have a work around, and are presently being used, making them potent, if not perfect.

6.4 Where can they be used?

UUVs can be utilized in numerous fields, as discussed earlier and seen in **Figure 2**. Similarly, the broad areas of utilization in the military have also been discussed. However, some specific military activities where UUVs can be utilized are (Berenice, n.d):

(a) To help address patrolling the impossible vastness of the world's oceans.

(b) To stealthily disable or destroy enemy vessels.

(c) For mine-hunting capabilities, using low-frequency broadband sonar to improve capability to find volume and bottom mines in high-burial and high-clutter environments.

(d) Engaging and stopping small vessels in the littoral environment, which otherwise are difficult to intercept and stop by naval vessels.

(e) To gather intelligence on enemy assets in the open ocean and in enemy harbor areas or under enemy waters.

(f) For coastal security of its own coast and harbors.

(g) For security of own assets in foreign waters against attacks by small crafts.

(h) To 'hold at risk' submarines while leaving and entering harbor and to trail and destroy them if required.

6.5 What is the infrastructure that will be required?

A launch and recovery system (LARS) is a basic minimum infrastructure required to utilize UUVs from ships, submarines, or piers. While a LARS is UUV specific, it would need to be fitted on piers and ships from which the UUV is to be operated. Currently, dedicated research vessels have these LARS and operate UUVs for various subsea activities that include ocean exploration (Agarwala, 2019). As for naval ships, their utilization presently is limited to pre-defined and pre-modified vessels that include a space for an operator console to control the ROV or the AUV. From a submarine, the option available is to launch from a torpedo tube, a missile tube, or from a dry container carried as a strap-on called a 'Dry Dock Chamber (DDC)'. However, submarines can only launch UUVs, while the recovery would need to be undertaken by a ship.

Currently, the US Navy launches and recovers UUVs up to Sea States 3, in accordance with STANAG 4194:1983, with platform freeboard not greater than 4.5 meters (Putnam, 2018). To increase the versatility of the launching ship in being able to launch a variety of UUVs ranging in size, weight, and make, a universal LARS is being developed by Great Lakes Sound and Vibration, Inc. (GLSV). Such a system would allow automatic recovery of the UUV, which presently requires human intervention. Once developed, the LARS will be operated from a Littoral Combat Ship (LCS) (Putnam, 2018). Similarly, Thales Australia and Flinders University have joined to develop an automated launch and recovery system for the Bluefin-9 AUV (Uppal, 2020).

It is critical to understand that, unless there are safe and effective systems for launch and recovery, these vehicles cannot be utilized safely and effectively, especially when the mother-ship is underway.

6.6 How will they be transported?

Since the cost of manufacturing of UUVs is high, and they are made of lightweight material such as composites, titanium, and a variety of aluminum alloys (Hyakudome, 2011), care needs to be exercised to ensure that they are transported with utmost care and with the correct packing/procedure as recommended by the manufacturer. While some of them, which are small (say gliders) and can be handled physically, may be easier to transport, others that are heavy (say an ROV) may require additional care. Furthermore, care and provisions need to be created to ensure that they are hauled out of the water once the desired operation has been completed. In addition, the requisite maintenance cycle would need to be provided once their current tasking has been completed.

6.7 How will they be tested and evaluated prior to use?

Capability-based short-listed vehicles would need to be assessed for various technical and operational parameters to perform a desired mission. This assessment could include propulsion design, battery power supply, sensors, navigation capabilities, vehicle interface program, reliability of operations, feedback from relevant operating environments, operating variables, etc. Care needs to be taken to make the testing credible, with defined measurable and testable parameters. In addition to these tests, if required, more challenging threats and environments can be incorporated without mandating the adherence of specific performance parameters.

6.8 What is the training required for operating these UUVs?

UUVs are state-of-the-art equipment and, hence, there is a need to understand their realistic capabilities and limitations based on the engineering facts and the physics governing each of the vehicle systems. Such an understanding would help deployment capability and limitations that can impact mission performance. This understanding is required at the operator, maintainer, and the planner level, and will need to be developed by theoretical and practical training at various stages of induction and operation. Today, many companies and institutions provide training to users on operating UUVs. However, for maintaining UUVs, the Original Equipment Manufacturer (OEM) would be best suited.

6.9 Where will they be based or distributed?

Like any resource allocation of the military, the distribution of these vehicles would be driven by requirement and threat perception. Initially, the trained manpower being limited, it would need to be moved around with the hardware. As these vehicles make inroads in the navy, the in-house expertise and knowledge would increase, thereby ensuring their much greater and uniform distribution.

6.10 How will they be maintained and supported?

Like any new technological equipment, in the initial years, the product would need to be supported by the manufacturer through appropriate 'All-Inclusive Annual Maintenance Contracts' or the like. In the longer run, necessary expertise for maintenance, repair, and exploitation would need to be developed, akin to what is done for the maintenance of ships and submarines currently. It would be even better if the UUVs of interest can be manufactured or licensed for production within the country. This would ensure better maintenance and technical support availability. Overall, the envisaged maintenance and support would be similar to what is experienced with the present induction policy for new technology.

6.11 What is the kind of manpower required for them?

The manpower requirement for these vehicles is expected to be less than that employed for similar activities from existing platforms (DoD, 2011) since these vessels are either autonomous or semi-autonomous. This is expected to result in manpower saving for operations. However, such a saving is expected only if the true potential of the vehicle is exploited. In the case where conventional procedures and systems of manning are employed, the expected manpower saving would not be achieved but would, in fact, demand a higher manpower.

6.12 What policy changes are required for their use?

It is a given that, if such state-of-the-art technology is to be used by the navy, certain policy guidelines and Standard Operating Principles (SOPs) will have to be developed and made available (Brett, 2019; Agarwala, 2021a). These would, logically, need to include the area, purpose, and bounds of their utilization, along with their expected gains. These definitions would help define the kind and number of vehicle(s) to be procured and the necessary support mechanisms to be made available.

6.13 Who is using it and for what gains?

Around the world, only a limited number of navies are utilizing the services of UUVs. The maximum usage is by the US and China (Humphris & Soule, 2019), with one challenging the other for supremacy. Though the US has been pioneers in developing the technology, China is catching up fast by beginning with 'reverse engineering' and then moving to the next level of 'innovative designing' that is, in some cases, leaving the US products behind (Agarwala & Chaudhary, 2021). The Russian Navy, on the other hand, has developed a nuclear-capable UUV named Poseidon for a special purpose nuclear submarine, Belgorod (Fortune Business Insights, 2021). Similarly, the PLAN may use UUVs for ASW and seabed operations, including submarine cable surveillance and tapping (Fedasiuk, 2021). Currently, the market supply of UUVs is limited to those from Western markets, but it is only a matter of time before Chinese products flood the market like has been seen in the market for aerial drones.

As for their usage, media reports indicate that both the US and China have been using them for intelligence gathering and surveillance extensively. The US have been utilizing their UUVs off the coast of China (Truver, 2012; Agerholm, 2016) and the Gulf region (Ervin et al., 2014), where their navies have been extensively employed, while the Chinese have been using theirs in the South China Sea and the Indian Ocean to monitor and gather intelligence on the littorals in the region (Agarwala, 2021b).

6.14 Where will these systems be deployed?

These systems can be deployed for various requirements, as indicated in **Figure 2**. The main gains for the navy from utilizing UUVs can be in dull, dirty, and dangerous operations that include intelligence gathering, surveillance, minesweeping, submarine cable survey, tapping and severing, and delivery of payload in conflict scenarios as a minimum. In essence, one can say that the three principal uses of UUVs for the navy are defensive (mine sweeping and Maritime Domain Awareness), offensive (payload delivery, laying mines, attack surface vessels), and intelligence (surveillance, intelligence gathering, tapping and severing submarine cables).

6.15 What are the associated operational risks of using UUVs?

The operational risk of using a UUV will be driven by the operation and the operational efficiency desired. However, as mentioned, since semi-autonomous UUVs are considered the best for military operations, the greatest risk in utilizing UUVs by the navy are the issues associated with carrying these vehicles onboard ships/submarines, and the associated human intervention required at sea to operate them that requires in situ adaptation. When operation is clandestine, the risk of mission-compromise exists. During mine classification and identification, the risk level is dependent on the bottom topography, the clutter of mines, the ocean floor debris, and the vintage of the mines.

One notices that these risks are consistent with the operational risks experienced by existing operations. The advantages that human life is not at risk and that operations, such as the classification and identification of vintage mines, can be undertaken with greater confidence makes them a candidate with minimum risk.

6.16 What is the associated cost in using a UUV?

Currently, the exact costing of UUVs is still a closely guarded secret. However, reports (SMRU, 2016) indicate that the cost of an AUV (autonomous UUV), considered the most expensive in the UUV family, is high. The average cost of building an AUV is around US$ 70,000, and the instrumentation may cost around US$ 5,000 to 10,000 per sensor. This may add up to US$ 2 - 6 million (as is the case with A18 AUVs from ECA group, France). In addition, the operating cost is estimated to be approximately around US$ 1,000 per day (Project Oceanography, 1999). Additionally, the maintenance cost of these platforms is also extremely high. However, since the cost of an equivalent ship is even higher, the disruptive nature and associated safety of personnel provided by AUVs makes them a viable option when compared to conventional ships. Since other forms of UUVs are relatively cheaper, due to limited automation, they are considered to be attractive options for naval operation when compared to equivalent ship platforms. The major drawback is that UUVs are task specific and cannot be used for one-size-fits-all situations.

6.17 Which one of these should be inducted into the navy?

While there are numerous models and types of UUVs (both ROVs and AUVs combined), the model to be inducted would entirely depend on the mission profile and the required range of operation. However, existing ocean observation systems, such as submerged floats, gliders, and tsunami warning buoys, can be used to collect ocean-based intelligence, even for military use, as has been displayed by China (Agarwala, 2021b). With technological advances of using seabed moorings as points for data transfer, charging, and communication, the effectiveness of UUVs in waters away from coasts can be enhanced.

6.18 Which is better, an ROV or an AUV?

Both ROV and AUV are functionally and operationally different, and have their own pros and cons. Their ranges and uses are entirely different, with the ROV being more like a microscope (for a detailed examination), while the AUV is like a telescope (for a wide area examination). However, to decide between the two, one needs to understand and consider the need for trained manpower and necessary and essential support systems, which vary between both these vehicles.

7. Discussion and analysis

In the preceding sections, we have discussed the need and the possible queries that need to be addressed prior to integrating UUVs into the navy. Studies have shown that UUVs are a technology which the navy cannot overlook for long. Since UUVs provide numerous benefits to the navy, such as lower costs of operation and maintenance, higher safety of personnel, and continuous data and coverage in all environments allowing use of manned platforms elsewhere, they need to be integrated into the navy at an early date. While the need of UUVs cannot be undermined, one needs to realize that, in trying to introduce them in the navy, only well-proven and established systems should be inducted. Since the market and the technology are still developing and expanding, untried systems in the name of new technology should be avoided.

It may be noted that the use of UUVs challenges the existing concept of ‘user-control’. While AUVs and gliders control themselves over extended periods of time, semi-autonomous vehicles and ROVs permit user interaction to a limited extent. Since UUVs are the future technology for maritime forces, it is essential that the user learns to accept the idea of giving up real-time control. Similarly, with the use of UUVs, the navy would need to accept expendability through acceptable loss of UUV platform(s) as the new working philosophy; however, to ensure accountability, some checks and balances would need to be instituted (Wernli, 2000).

Even though there are numerous types of UUVs that vary in size, weight, complexity, and capability, it is important to accept that one UUV cannot provide all capabilities and, hence, the type of the vehicle to be selected and used will entirely depend on the operational mission to be achieved. With increasing operational experience, identifying the preferred type of vehicle would be possible, along with defining new features to be developed.

Currently, the market has some small, low cost vehicles that inevitably require mother-ship support, due to limited endurance at one end of the spectrum, and some very large costly systems that can do the unthinkable, but are huge and bulky, at the other end. Even though both of these segments have their own market utility, only time will dictate which one of them will survive in the long run (Blidberg, 2001).

With technological development of UUVs in the hands of academia and the commercial industry, the capabilities available with UUVs greatly outscore the ability with fleets. This thus makes conventional navies vulnerable to attacks. It is, thus, essential that careful decisions and investments are made today, to make UUVs become significant contributors to the navy’s capabilities tomorrow, and be ready for the unexpected future (Fletcher, 2000). Such vehicles would act as force multipliers by sensing, tracking, identifying, targeting, and destroying an enemy- all autonomously- and tie in with the full net-centric battle-space. In addition, they would act as risk reduction agents for life-threatening operations for the navy of the future (DoD, 2004).

As a basic minimum, by utilizing UUVs for intelligence, surveillance and reconnaissance missions, inspection and identification, payload delivery, and time critical strikes, we are only extrapolating their utilization in areas where unmanned platforms have been utilized successfully in air and on ground. While the maritime domain still grapples with the acceptance of unmanned platforms, both autonomous and semi-autonomous, technological developments continue unabated. The time is not far when other technologies, such as RILS (reacquire, identify, and localize swimmers- for threat from frogmen) (Evans, 2010) and underwater docking stations (Yazdani et al., 2020) (for charging and data transfer of information from UUVs) would be available.

Even though the associated costs and the high maintenance may be downsides, the ability to use the technology to carry out dull, dirty, and dangerous missions without putting human operators in danger acts as encouragement for the utilization of UUVs. It is opined that the missions assigned to UUVs will grow exponentially as trust in the systems becomes commonplace, akin to the growth seen in smartphones.

8. Recommendations

In this article, some answers have been provided to questions that arise in the minds of decision makers from time to time when trying to evaluate and/or induct an unmanned underwater vehicle. Though the questions and their answers may seem outright simple and straightforward, they are considered important to address the possibility of integration of UUVs in naval applications. To summarize the understanding of these unknowns for a fruitful discussion, it is recommended that:

(a) The type of the UUV to be integrated into the navy needs to be based on the operational requirements, since the current breed of UUV is task specific. A UUV designed for ISR cannot be used for payload delivery, and vice-versa. Hence, it is important to be specific about the requirements before initiating further debate on its selection. However, when more than one task is envisaged for a single UUV, the use of task modularity is considered to be an option, and the available task modules available for the UUV under consideration may need to be included in the acquisition.

(b) Once the requirements have been defined, it is important to shortlist proven designs, rather than experimental designs. At times, these may seem to be more expensive than experimental ones, but their long term cost would turn out to be less due to proven technology and the availability of technical support, as against a design that is experimental.

(c) It is critical to mention that a new technology like UUVs is not cost effective for power projection but for actual use. In case the actual use itself is debatable, it may be prudent to reconsider the decision.

(d) Since this technology has numerous applications, both in military and civil areas, it is essential to nurture and encourage its growth within the country. Such a step would ensure self-reliance towards the essential upkeep and upgrades over its life cycle of 20 - 25 years and ensure ready availability of the product within the nation.

(e) Such advanced technology requires trained manpower, both at the operator and the maintainer level. These, thus, need to be organized and made available when the integration actually happens.

(f) Once the need is defined and accepted, it is the available budget that will define how, when, and if UUVs can be integrated into the navy. While making this decision, the long term operating cost of a UUV and a conventional platform over the design life should be compared, rather than the initial cost, to better appreciate the gains of integrating the UUV in naval applications.

It is essential to understand here that this is a generalized summary for the induction of new technology and will become specific when specific details and inputs are incorporated. Once the 'devil in the details' evolves, more and more specific questions will arise, which will help refine the decision making of integrating UUVs for naval application.

9. Conclusions

As the involvement of humans increases with the oceans, the need for Maritime Domain Awareness has increased. This effort requires new tools and provisions for a real-time MDA picture. In order to get such a picture, the importance and the requirement of autonomous and unmanned systems cannot be but emphasized. Though numerous questions about tracking and control across platforms and existing network systems need to be studied and resolved, there is no doubt that these vehicles are the future of maritime surveillance and numerous other dull, dirty, and dangerous activities at sea (Healey et al., 2007).

As UUVs are increasingly deployed to conduct highly dangerous missions that have never been possible for legacy naval systems, they stand to fundamentally alter the way wars will be fought. This requires that ways and means of inducting this future technology into the navy be discussed at large to create mechanisms and conditions that would help absorption of this technology.

Accordingly, some basic and pertinent questions that come to mind as knowledge gap areas in the conceptualizing, acceptance, and induction of such a technology have been discussed. By no means are the questions raised and the answers provided comprehensive and complete, but they provide a start point for a debate to be initiated. In the present state of affairs, technology has delivered; it is the lack of imagination that is holding back the realization of the true potential of UUVs.

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