Global Developments in Sea-based Unmanned Crafts

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Sea-based unmanned crafts are increasingly being used by navies across the globe because of their utility and multi-mission capabilities. The future of naval warfare will be driven by unmanned systems thereby reducing the risk to human lives. This article explores the sea-based unmanned crafts that includes a survey of Unmanned Surface Vehicles (USVs) and Unmanned Underwater Vehicles (UUVs) for military use. It includes a description of sea-based unmanned crafts, the present doctrines and standards, technology advancements and applications. This work presents the challenges and legal issues in deploying such technologies, global developments with their typical applications and the prospects of their applicability. In the future, it is believed that with the imminent fusion of the military–civil and the academia, unmanned systems will be used widely in civil and military matters.

Keywords: *Unmanned Surface Vehicles (USVs), Unmanned Underwater Vehicles (UUVs), Autonomous Navigation, Artificial Intelligence (AI), Swarm Computing*

Unmanned and autonomous systems are advertently becoming an intrinsic part of the armed forces. In recent times, drones/Unmanned Aerial Vehicles (UAVs) have been in much debate, which has only gained momentum due to their intrinsic applications in the defence and commercial market spaces. However, some latest developments towards sea-based unmanned crafts have generated much interest. Navies worldwide are increasingly interested in unmanned sea-based

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crafts for explorative, exploitative and as a force multiplier for military operations. Given the geopolitical environment and scope of future conflicts expected in littoral regions, the focus of the navies across the globe is increasingly shifting towards research and development in the field of sea-based unmanned crafts. Because of their autonomous nature and capability of working in a network-centric environment, they are increasingly being adopted and efforts towards their development are being exacerbated. It is expected that developments in technologies like Artificial Intelligence (AI), swarm computing, and quantum computing will provide capabilities to control a swarm of weaponised Unmanned Surface Vehicles (USVs) and Unmanned Underwater Vehicles (UUVs), which will revolutionise naval warfare. The Defense Advanced Research Projects Agency's (DARPA) Explainable Question Answering System (EQUAS) is focused on explainable AI, which builds the trust of the users in the system. It provides them with pertinent information on how decisions are being made so that they can understand the decision-making processes and the system recommendations.[1] Another project of DARPA is Ocean of Things, which collects and analyses information from float sensors to train the USV and UUV AI systems for real-time operations.[2]

This article tries to outline recent advancements in this field delineating technological developments, challenges and future trends. It further reviews the unmanned sea-based crafts, both USVs and UUVs, doctrines and standards, technological trends, applications, challenges, legal issues, policy considerations and developments made over the years. The article also attempts to understand the latest technological aspects and challenges faced by the navies across the globe and imperatively focuses on the developments made primarily for military use and the battlefield.

Background

Considerable progress has been made in the field of Sea-based Unmanned Crafts over the past few years, so much so that they are now considered a critical component, which will eventually revolutionise the battlefield in future naval warfare. Unmanned sea-based technology encompasses surface vehicles and submersible vehicles that do not have any human intervention and are classified as USVs and UUVs. They can either be operated remotely or in an autonomous fashion to perform surface or underwater patrolling and surveillance missions.

Unlike the remotely operated vehicles, which require human intervention, the autonomous ones are self-regulated and do not require any human involvement for carrying out activities. These vehicles have varied military and commercial applications and are used for oceanographic research, sensing, mapping and collecting data. Military applications include intelligence, reconnaissance and submarine warfare, etc. They are particularly essential arsenal for navies across the globe, which aim to possess effective weapons with additional military capabilities involving minimal human intervention and operability in high-threat environments.

Brief History of Sea-based Unmanned Systems

The use of unmanned sea-based systems dates back to the World War II wherein, they were used limitedly for mine clearance and damage assessment. In 1957, the first UUV Self-Propelled Underwater Research Vehicle (SPURV) was developed and classified as an Autonomous Underwater Vehicle (AUV) by the United States (University of Washington) in the Arctic waters to collect oceanographic data. Since then, technological advancements have resulted in the development of SPURV II, in 1979 which resulted in better performance and operating time with large number of sensors and recording devices. In 1974, a group of scientists from Institute of Automation and Control Processes developed an AUV called "SCAT" and further modifications led to development of L1 and L2 AUVs for testing and developing technologies for oceanographic mapping and data collection.[3] Further in 1983, the introduction of Autonomous Remote-Control Submarine (ARCS) brought improvements in battery life, navigation and communication systems. In addition, the use of solar-powered AUV (SAUV) stimulated long-term explorative missions.[4] Other examples of sea-based unmanned systems include Jason Remotely Operated Vehicle (ROV), Remote Environmental Monitoring Units (REMUS), and Girona 500 I-AUV, which have worked successfully in the waters with increased modern sensing, navigation and communication capabilities to carry out pre-planned acoustic commands and autonomous inspections.[5] Similarly, USVs were developed for minesweeping and damage assessment. In 1946, during crossroads operation, drone boats were used to collect samples of radioactive waters after the atomic blasts. Similarly, in the 1960s, a fibreglass hull was modified and used to remotely control "Chain drag" minesweeper.[6] By the 1990s, considerable advancements driven by the paradigm shift of the Navy towards research and technological progress were made in the maritime domain towards USVs and UUVs. Specifically, in the 1990s, a Remote Mine Hunting prototype was made operational in the Persian Gulf for 12 days for mine-hunting operations. Thereupon, the US Navy shifted its focus to littoral warfare and anti-terrorism missions and in 2001, the US Office of Naval Research proposed the concept of Littoral Combat Ship (LCS).[7] After the success of such systems and their ability to be stealthy and persistent—both manned and unmanned—there had been a keen interest in the development of UUV technologies.

Doctrine and Standards for Sea-based Unmanned Systems

The US doctrine on unmanned systems emanates from varied sources like the Unmanned Systems Integrated Roadmap FY 2011–2036 and its updated version, the Unmanned Systems Integrated Roadmap FY 2017–2042,[8] the Navy Unmanned Undersea Vehicle Master Plan (2004),[9] the Navy Unmanned Surface Vehicle Master Plan (2007)[10] and the Navy Large Unmanned Surface and Undersea Vehicles: Background and Issues for Congress (2022), etc.[11] These sources cover seven capabilities (discussed in the next section) presented in the integrated roadmap and discuss issues related to unmanned systems referring to them as crafts.[12] Due to this, there are issues related to navigational rights, immunities, international maritime legal regimes and weaponised Unmanned Maritime Systems (UMS).

The unmanned systems integrated roadmap discusses the overall system integration processes encompassing aspects of technology, engineering, fleet experimentation and life cycle support. It also elucidates improvements across Doctrine, Organisation, Training, Material, Leadership, Personnel, Facilities and Policy (DOTmLPF-P) spectrum. The updated version of the roadmap has consolidated major advancements into four themes: Interoperability, Autonomy, Network Security and Human-machine Collaboration. It also provides a comprehensive view of the alignment of strategic guidance and unmanned systems goals with the strategic vision of the US Department of Defense. The integrated strategy is focused on technology thrusts and programme deliverables for the four classes (discussed in the next section) and expresses the need for coordinated technological investments with commonality and modularity standards. These standards, it is envisaged, will act as critical enablers towards realising the vision of unmanned systems common control and include Unmanned Systems C2/Interoperability Standards, Unmanned Systems C4I Communications Standards and Unmanned Vehicles Size/HM&E/Payload Modularity Standards.

The Chinese People's Liberation Army (PLA) does not have any specific term for doctrine. However, the People's Liberation Army Navy has its operational theory and operational concepts for sea-based unmanned crafts. It has a PLA Navy (PLAN) component called the Offshore Defense. PLA has identified 22 PLAN campaigns it could follow in case of a conflict.[13] These are Sea Blockade Campaign, Sea-to-Land Attack Campaign, Antiship Campaign and Naval Base Defense Campaign, which includes attacks with nuclear, biological and chemical weapons.

The United Kingdom (UK) has a joint doctrine on UK Maritime Power that provides a comprehensive roadmap of maritime forces, their strategic requirements and how they can contribute to joint actions. It also examines the maritime force capabilities such as war fighting, maritime security and defence engagement.[14] While there is no specific doctrine on unmanned systems, the same discusses aspects of surface fleet and anti-submarine warfare that function autonomously for extended periods.

The document also presents the maritime contribution to military power in various forms like the surface fleet (aircraft carriers, frigates and destroyers, amphibious shipping, mine countermeasures vessels, oceanographic survey vessels, patrol vessels, etc.), Submarine Service (nuclear deterrence and nuclear-powered attack submarines), Fleet Air Arm, Royal Marines and Royal Fleet Auxiliary.

In the past decade, introduction of unmanned operations across militaries has highlighted the role of manned and unmanned teaming as an important topic of discussion. There are various ongoing programmes with unmanned systems (UUVs, UAVs and Unmanned Ground Vehicles [UGVs]). Moreover, navies across the world are coordinating such programmes for shipboard integration into naval platforms. Powerful navies, like that of the US, have had only limited success in the integrated unmanned system.[15] The navies, therefore need to focus on integrating Unmanned Aerial Systems (UAS) into manned operations as well. The government and industry standards with the American Society for Testing and Materials (ASTM) and International standards and the Association for Unmanned Vehicle Systems International (AUVSI) are the recommended standards for joint interoperability.[16] However, UUVs/AUVs have limited standardisation with no ISO standard (International

Organization for Standardization) and are derived from ROV rules.[17] The AUV performance evaluation comes under the US National Institute of Standards and Technology, euRathlon and European Robotics League. The successful integration of unmanned systems into the "Systems of Systems", hence requires the development of effective tactical doctrine with a network-centric framework for joint manned and unmanned deployment.

With changing geopolitical environments, maritime threat environment is also rapidly changing. Countries like China are rapidly advancing their maritime power and matching their crafts with that of the US. Similarly, the focus of other maritime nations has also shifted towards adoption of unmanned vehicles with air and sea capabilities. Sea-based unmanned vehicles' diverse roles and applications have made them essential for battle preparedness. It is believed that the future of battlefields will be spearheaded through autonomous weapons, making it a decisive strategy for nations.

Sea-based Unmanned Vehicles: Technology Advancements, Doctrines and Standards

Sea-based Unmanned Vehicle technology has made immense progress in the past decade with navies coming up with Master Plans for surface vehicles and underwater vehicles. One such instance is the US Navy's Master Plan for surface vehicles, which came up in 2007.[18]

With limited technology, it was difficult and expensive to achieve precision navigation and control in the past. However, with new advancements, the focus is now on efficiently and affordably integrating autonomous systems. The US Navy, in the Congressional Research Service Report updated in January 2022, has identified five key enabling technologies for its USV and UUV programmes that would fit well with any navy around the world envisaging to build its naval fleet successfully.[19] Considering the limitations on underwater communications, which are not very effective due to the low range of radio-frequency electromagnetic waves, the implementation of autonomy relies on new-age technological advancements in sensor systems, propulsion technologies, AI, data science, computer vision, machine learning and deep learning. Following have been identified as key technology enablers[20]:

- *Endurance*: One of the prime technology enablers is the endurance mechanism of the unmanned systems that includes reliability, safety, high range, efficient sensors and other additional support;

- *Autonomy and Precision Navigation*: This includes varying autonomy and decision-making levels with increased accuracy and efficiency;
- *Command, Control and Communications*: This key technology enabler defines the safe and reliable launch and recovery of sea-based unmanned systems autonomously while following the standard command, control and communication process;
- *Payloads and Sensors*: It comprises the augmented capability and capacity for sensors and payloads; and
- *Platform Integration*: This is the driving technology enabler for achieving autonomy as integration includes enhanced synchronisation with host platforms and building the launch and recovery capability of the unmanned systems.

Figure 1 shows the triad of Learn, Transition and Standardise that define the adoption of key technology enablers to achieve an increased level of maturity of sea-based unmanned systems.

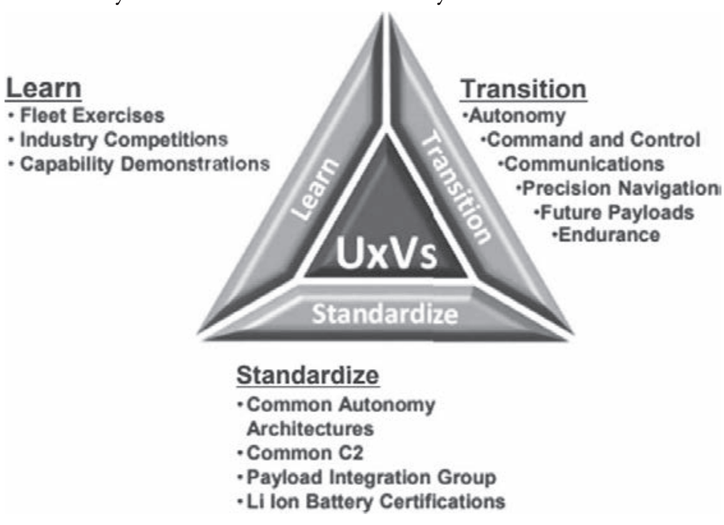

Figure 1 Enabling Technologies for USVs and UUVs

Source: CSR Report 2022[21]

The autonomous sea-based vehicle technology is still in its infancy. Considering the technology maturity model stating the levels of autonomy as shown in Figure 2, there are many levels of autonomy where Level 1 is simple automation and Level 10 is the conglomerate autonomy. There is still a long way to achieve full trusted self-regulating autonomy with no human intervention.

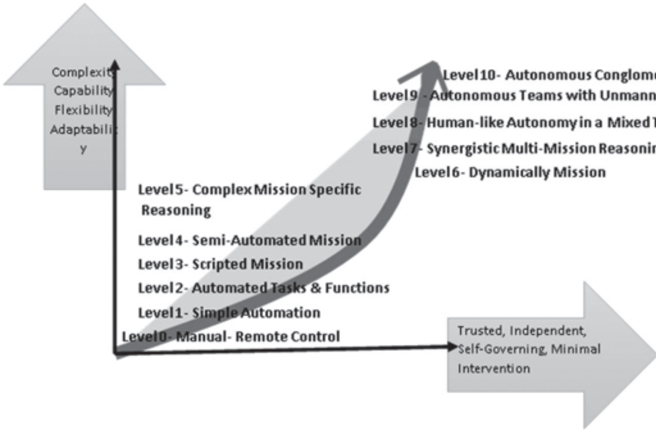

Figure 2 Levels of Autonomous System

Source: R.K. Nichols et al., 'Underwater Autonomous Navigation & Other UUV Advances [Mumm]', p. 109.[22]

The basic scheme of navigation guidance and control architecture for sea-based unmanned craft is shown in Figure 3.

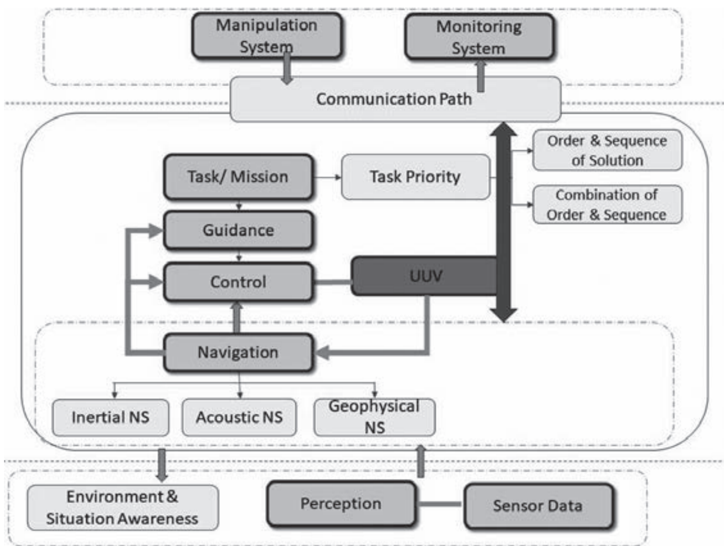

Figure 3 Schematic Diagram of Mission, Planning, Navigation, Guidance and Control for Sea-based Unmanned Crafts

Source: Adapted from Asgharian Pouyan and Zati Hakim Azizul, 'Proposed Efficient Design for Unmanned Surface Vehicles'; Muniyandy Elangovan, 'Basic Design for the Development of Autonomous Underwater Vehicle', pp. 12–17.[23]

Unmanned Surface Vehicles (USVs)

The proliferation of stealth technology has shifted focus towards USVs and has advertised the navy's needs. USVs have not been in much use for lethal missions in the past and were majorly used for Intelligence, Surveillance, Reconnaissance (ISR) and minesweeping activities. With the proliferation of stealth technology, USVs have now gained the potential for stealth and lethal missions as they are less detectable. The small-sized USVs like Very Small USVs (VSUSVs), Small USVs (SUSVs) and gliders are best suited for a single type of mission like ISR activities.[24] Various stealthy USV sensor platforms based on high speed, high payloads with small crafts designed to meet the capabilities of multiple missions have been proposed to help serve the unmanned systems to protect surface ships against anti-ship missile threats.[25]

There are various craft types in USVs like semi-submersible crafts, conventional planing hull craft, semi-planing hull craft, hydrofoils and others. The hull forms have specific features that make them suitable for certain operations.[26] The changing requirements and adoption of unmanned systems have brought innovative and new hull forms. The 2022 CRS report states that the navy wants to acquire Large Unmanned Surface Vehicles (LUSVs) and Medium Unmanned Surface Vehicles (MUSVs) as a part of an effort to shift the navy to new fleet architecture.[27] The US Navy Unmanned Surface Vessel Master Plan of 2007[28] characterises various Joint Capability Areas (JCA) of USVs and has divided the vehicle classes as X class, Harbor class, Snorkeler class and Fleet class. X class is a small non-standard class of systems with limited ISR capabilities based on 11m Rigid Inflatable Boat (RIB); Harbor class is based on navy standard with 7m RIB with robust ISR capabilities with lethal and non-lethal armament; Snorkeler class is approximately 7m Semi-Submersible Vehicle (SSV) with Mine Countermeasures (MCM) towing missions and Anti-Submarine Warfare (ASW Maritime Shield) for carrying out stealth missions; Fleet class is the purpose-built USV used for handling different types of equipment with weight limitations of 11m RIB. The various variants of this class can be used for MCM sweep, ASW and high-end surface warfare missions. The various applications of USVs in defence as per the JCA includes Mine Countermeasures, Anti-Submarine Warfare, Special Operations Forces Support, Electronic Warfare and Maritime Interdiction Operations Support.[29]

Unmanned Underwater Vehicles (UUVs)

UUVs have become a valuable asset for underwater battlespace due to their operational capabilities requiring minimum technical or logistic support. These systems do not require any external signals or tracking systems and operate at variable depths for long periods. Another advantage of AUV is its accessibility to operate covertly in geographical constraints where ROVs and other towed bodies cannot operate.[30] The modern-day UUV uses fibre optic imaging for sending electronic images to the crew and capabilities like Sound Navigation and Ranging System (SONAR) that works both in active and passive modes. In addition, the UUV uses inertial guidance and navigation systems like gyroscope and Strapdown Inertial Navigation System (SINS) to track the UUV's motion and geographic position changes. The challenges with the UUV system are the complexity of autonomous navigation that requires error-free navigation and guidance systems as even a small error in measuring capabilities can cause significant deviations in the information that the guidance system will eventually provide. Another challenge is the power requirements of UUV systems and the level of difficulty in communicating underwater, due to instability in the signals and disruption from marine/sea-life. Also, the environment where the UUVs operate is unstructured causing navigational difficulties related to identification of specific landmarks, operating in dark with complete reliance on sensors. Considering these challenges, continuous research and developments are being carried out in the field of UUVs and AUVs.

The recent progress in propulsion, control, hydrodynamics and sensor technology have brought significant innovation in this industry. Advanced systems like new Acoustic Navigation Systems, Simultaneous localization and Mapping (SLAM) Methods, Integrated Navigation Method of SINS, Doppler Velocity SONAR and data fusion capabilities have led to successful underwater missions in a more affordable manner.[31] Furthermore, the advancement in strategic submarine navigation systems like Esri's launch of the Ocean Geographic Information System (GIS) initiative in 2012 has provided practical solutions for visualising and analysing ocean information like seafloor mapping, habitat mapping, shoreline analysis and geomorphic research. These GIS systems will also help study climate change, analysis of risk due to coastal floods, hurricanes and marine debris mapping.[32] The UUV industry research revolves around the small sized UUVs of a few metres in length to extra-large unmanned undersea vehicles (XLUUVs) for long-endurance surveillance missions or for delivering payloads and other UUVs. The defence industry is also exceedingly working towards developing UUVs like the "ORCA" project (The US Navy's Extra Large Unmanned Underwater Vehicle [XLUUV] programme) and MCM programme to add capabilities in the existing systems or replace them with new AI-based UUVs for ISR and ocean warfare. AUVs have been mainly used for defence applications and extended to other sectors for inspection, research, seabed mapping, geological sampling, oceanography, payload delivery, water mine search and disposal and more.[33] In the defence sector, UUVs and AUVs have been extensively developed for ISR, time-critical strikes, nuclear power plant inspections and ASW.[34]

Latest Defence Technology Advances: USVs and UUVs

The technology advancements in sea-based crafts have a significant lineage in the defence sector as it offers navies flexibility and increased operational time and safety in dangerous environments. Some of the latest technologies being implemented in the UUVs are listed below:[35]

- *Maritime Swarm Technologies*: The networking of unmanned marine resources will be a vital tool in the future battlefield where the formation of clusters in the form of swarm drones will be used for decoying, surveillance and data gathering. One such example is the Cooperative Autonomous Swarm Technology (CAST) Program by the US Department of Defense Officer Naval Research (ONR), which is developing technologies on cooperative operations of unmanned maritime systems. This programme includes research and development in bio-inspired group behaviours, collaborative navigation, homogenous and heterogenous groups, fault management and counter swarm.[36] Another example of swarm technology being implemented in maritime crafts is the Long-Range Unmanned Surface Vessel (LRUSV) by Metal Shark that works in clusters, delivering swarms of attack drones to hit targets at sea and land.[37]
- *Quantum Technology for Underwater Communication and Navigation*: Quantum computing technologies have been gaining momentum in the UUV field, where many investments are being made to develop quantum sensors that will improve the navigation capabilities of UUVs and AUVs significantly. As GPS cannot be used underwater, quantum sensors meet the navigational needs perfectly and are being used in inertial

navigation systems and provide excellent capabilities for threat detection like mines and anti-submarine warfare. Quantum communication and quantum cryptanalysis will be significant areas of consideration for the future of defence technologies as they will be used extensively for secure communication with unmanned systems.

- *Artificial Intelligence*: The raging use of AI in almost every industry has turned out to be an enabler for deriving meaningful information and decision-making. In maritime industry also, AI is being used extensively for achieving complex capabilities like obstacle recognition and autonomous navigation. The market has seen a significant transformation with the introduction of AI-enabled unmanned vehicles. The data collected from sensors is analysed to draw meaningful insights enabling decision-making for complex capabilities like autonomous navigation, obstacle detection and prevention. The commercial and industrial sectors have made significant progress by successfully implementing AI-enabled autonomous systems. The defence sector is also designing and integrating AI into its systems to improve the warfighting doctrines.
- *Anti-Collision Technology*: In the maritime environment, anti-collision technology ensures safe navigation in dense zones and enables autonomous navigation in restricted areas. There are different types of sensors used for UUVs and USVs like SONAR, Light Detection and Ranging (LIDAR), an inertial sensor, pressure sensor to avoid collision and ensure safe navigation.
- *Mothership*: Mothership can be defined as controlled autonomy where the control of the fleet will rely on the mothership. It will function as the command-and-control centre for drone systems operating in that area. Many navies such as those of the US, Russia, Japan and Singapore have already assigned their ships with this concept.[38] In addition, navies are also looking at re-purposing their existing platform to serve as the mothership and operate the USV and UUV fleets.

Development of Sea-based Unmanned Crafts

The USV market size is expected to grow from US$ 616 million in 2021 to US$ 1,038 million by 2026 with a Compound Annual Growth Rate (CAGR) of 11.0 per cent during the forecast period. This number is low in comparison to the unmanned underwater market, which has reached US$ 3.6 billion in 2021 with a CAGR of 15.8 per cent and is expected to reach US$ 9,502.7 billion by 2028, exhibiting a CAGR of 17.59 per cent during the forecast period.[39] The navies across the globe are targeting to develop and procure low-cost, high-endurance UUVs as a replacement for deep sea drilling operations, anti-surface warfare and for carrying various modular payloads. However, the high operating cost and initial capital investments in UUVs and AUVs could impede the UUV market revenue growth to some extent.

In the commercial sector, USVs and UUVs equipped with sensor payloads are being used for applications like oceanographic research, data mapping, seabed mapping, debris mapping and geological sampling. The key players in the USV market are L3 Haris Technologies (UK), Textron Inc. (US), Teledyne Technologies (US), Elbit Systems and Rafael Advanced Defense Systems Ltd. (Israel). Some key players operating in the global unmanned underwater market are Saab AB, Lockheed Martin Corp, Kongsberg Gruppen, Atlas Elektronik GmbH, General Dynamic Corp, BAE Systems, Bluefin Robotics Corp and Oceaneering International.[40] It is expected that the electric segment in the propulsion sector and the sensors segment in the payload sector will expand due to higher demand and increasing integration in future. The electric segment is expected to register the highest CAGR due to its reduced complexity in power distribution architectures. In 2021, Saab Underwater Robots have joined Ocean Infinity's Armada Fleet by selling 10 of its new electric Work Remotely Operated Vehicles (eWROV).[41] RTSys has partnered with IM-Solutions and IES to develop Continuous Environmental Monitoring At Sea (CEMAS), an autonomous mobile surface station capable of deploying several of RTSys' NemoSens micro-AUVs for environmental survey applications like monitoring wind farms, surveillance of ports and coastal works, environmental monitoring (water quality, fauna, flora and chemical parameter in aquaculture) and installation of infrastructure.[42]

North America has accounted for the highest revenue compared to other regional markets in the past year. However, it is expected that Asia-Pacific regions like India, China, Japan and South Korea are likely to register significant growth in the USV and UUV markets. The maritime forces of these countries have increased their military spending with an increased amount of purchases being made in this sector.[43] The NATO ally countries signed a declaration of intent on Maritime Unmanned

Systems in 2018 and in 2019 France joined this initiative. In 2023, the Belgian and Dutch navies will replace their ageing sea-based crafts under the MCM programme and equip their fleets with 15 Inspector 125 USV, 20 A18-M AUV, 14 SEASCAN, 42 K-STERC ROV and 10 UMS Skeldar V-200 UAVs.[44] Elbit Systems will be providing Seagull USVs to Asia-Pacific countries to undertake mine countermeasure operations and anti-submarine warfare.[45] In future, the defence sector is expected to hold a significant share of the USV and UUV market.

Developments in the US

The US Navy has updated its UUV Master Plan and has identified 9-sub pillar capabilities as ISR, Mine Countermeasures, ASW, Inspection or Identification, Oceanography, Communication/Navigation Network Node, Payload Delivery, Information Operations and Time Critical Strike.[46] The US Navy dominates the seas with 68 nuclear-powered submarines, 11 aircraft carriers and more than 450 ships like destroyers, cruisers and support ships. In the CSR report of 2021, the US Navy states its inclination to employ accelerated acquisition strategies for procuring LUSVs and XLUUVs and the development of enabling technologies and concepts of operations for these unmanned vehicles.[47] The prototype to develop USV is called Ghost Fleet and its LUSV development within it is called Overlord. One such prototype is the medium displacement USV called Sea Hunter. The Sea Hunter USV has sailed without a crew from California to Hawaii and back again, navigating by AI using data from the vessel's onboard sensors, radars and cameras.[48] In May 2019, the US Navy formed a Surface Development Squadron to develop operational concepts for LUSVs and MUSVs, which consisted of Zumwalt (DDG-1000) class destroyer and one Sea Hunter. The US Navy has recently conducted successfully underwater explosion shock test on Unmanned Influence Sweep System (UISS). The test was conducted by the Aberdeen Test Center and Naval Surface Warfare Center (NSWC) Carderock with assistance from Textron and NSWC Panama City. The shock trials tested the survivability of UISS and its ability to execute missions in hazardous environments.[49] An unmanned underwater vehicle squadron-1 (UUVRON-1) has been formed to test the UUVs and development of the operation concept of UUV. Two test vehicles—LTV 38 and LTV 48—have been simulated to Light Detection Unmanned Underwater Vehicles (LDUUVs) and are also working with the XLUUV prototype. The US' XLUUV named ORCA, the largest XLUUV with advanced capabilities to perform several combat missions, including anti-submarine and anti-surface warfare, is unmatched. Other countries have now started to manufacture their XLUUV considering the US power and control in the sea. A new variant of Sprint-Nav hybrid navigation system for USVs and UUVs by Sonardyne was released in 2021. It is designed on anti-collision technology and works without external position reference at increased altitudes.[50] The Pentagon 2020 budget has cited increased funding for autonomous weapons programmes and has requested a 10-fold increase in UUV development with advanced AI capabilities. The requests total US$ 3.59 billion on unmanned undersea systems and US$ 4.47 billion on unmanned surface vehicles across the services, plus another US$ 900 million on AI.[51] Table 1 presents the capabilities of the US Navy's USV and UUV systems with their classification.

Table 1 Capabilities of Common USV Hulls and UUV Systems

Classification	*USV*		*UUV*	
	USV	*Capabilities*	*UUV*	*Capabilities*
Very Small	GARC Optionally Manned	ISR, Communication Relay, Armed Coastal Patrol	–	–
	ADARO/ MUSCL	ISR	–	–
	TBD	ISR, Comm Relay, Armed Escort	–	–
Small	MHU 1-4 w/ AN/AQS-24	Mine Hunt	MK18 Mod 1 (Sword Fish)	Mine Warfare (MIW), Intelligence Preparation of the Operational Environment (IPOE)
	USV w/Sweep Payload	Mine Sweep	IVER	Battle Space Awareness, IPOE
	USV w/ Hunt Payload	Mine Hunt	Sand-Shark Micro AUV	Battle Space Awareness, IPOE
	USV w/Mine Neutralization Payload	Mine Neutralisation		
	MCM USV	Mine Sweep, Mine Hunt, Mine Neut, Comm Relay, Counter Piracy, ASW, ISR		

Medium	MDUSV/ Sea Hunter (SH1)	ASW, Autonomy, Multi-Mission	MK 18 Mod 2 (King Fish)	MIW/ IPOE
	Sea Hunter (SH2), MUSV	ASW, ISR, Comm Relay, Counter Swarm	LBS AUV	Battle Awareness, IPOE
	Medium USV TBD Hull Form(s)	ASW, AUW, EW, MCM, Mining, Armed Escort, ISR, Counter Swarm	LBS-G	Battle Awareness
			Knifefish	Buried and Volume Mine Hunting
			LBS-AUV(S) RAZORBACK	Battlespace Awareness, MIW/ IPOE
			P3I, Future Blocks/Mods	Near Real-Time Mission Analysis, Improved Capabilities & sensors
Large	Ghost Fleet Overlord LUSV	ISR, SUW, EW, ASUW, Technology Maturation, CONOPs & Payloads	ONR Innovative Naval Prototype	Experimentation, Endurance, Autonomy, payloads
	Large USV TBD Hull Form(s)	EW, IST&T, Payloads, ASW, ASUW, Logistics [Fully Autonomous, Coordinated ops, operates OTH]	Snakehead Ph1 Vehicle	IPOE, Concept of Operations (CONOPS), ISR
			Snakehead INC1	Extended Range IPOE, Extended Range ISR, EW, Payload Integration ASW, ASUW
Extra Large	–	–	ONR Innovative Naval Prototype	Experimentation, Endurance, Autonomy, Payloads
	–	–	ORCA	MIW, CONOPs Development, Payload Integration
	–	–	XLUUV Future Capabilities	MIW, ISR, Strike capability, Payload Integration, MCM, ASW, EW, ASUW

Source: Based on US CSR Report 2022.[52]

Developments in China

China has recently overtaken the US in numbers with more than 500 ships, but their naval capabilities are still lagging behind compared to the US. China has been open about developing AI-based undersea systems and the prospects of underwater cities operated by robots to spearhead their military transformation to become the strongest in the world.[53] Currently, Chinese investment in AI-based research is the largest globally and a massive amount is being spent on sea-based unmanned systems. China's 912 Project focuses on developing AI-driven unmanned submarines for mine laying, surveillance, and attack mission.[54] China is also coming up with its 100-foot long XLUUV that will be deployed in 2022.[55] In 2019, China displayed its Large Displacement Unmanned Underwater Vehicle (LDUUV) "HSU001", which is 7m long designed for ASW and Intelligence Preparation Of the Environment (IPOE).[56] HSU001 lacks capabilities of large scale payload integration, however, it can be used for deploying small or micro UUVs. In terms of USVs, China has made advancements in AI-enabled USV, which they plan to use for patrolling and bolstering its territorial claims in the South China Sea.[57] Another USV named Tianxing no. 1 was developed by Harbin Engineering University and Shenzhen Hisibi Boat company. Its length is 12.2 meters and it is equipped with a hybrid power system and can perform high precision tracking of the target with advanced control. It can independently track dynamic suspicious targets and can be used for marine police patrol as well as marine hydrometeorological monitoring and seabed scanning and mapping.[58] M80 USV, 4.8 meters trimaran ship, which can be operated remotely as well as autonomously and has stealth capabilities by staying invisible at a wave height of 5m. Haiyi No 1 USV is another autonomous vessel developed by CSIC 701 and Wuhan University of Technology equipped with collision avoidance technology and ultra-short wave wireless communication support. Its applications include autonomous patrol and search forensics under complex environments.[59] Under the PLA's military–civil fusion programme, the Tianjin Binhai Artificial Intelligence Centre, has been established, in collaboration with the PLA's Academy of Military Science, which is working on the development of autonomous undersea drones.[60]

Developments in the UK and Other Countries

The UK's Defence and Security Accelerator (DASA) and the Defence Science and Technology Laboratory have developed Vigilant Forward-

Looking SONAR as a part of Uncrewed Underwater Vehicle Testbed.[61] Soanardyne and Wavefront have together developed a technology for underwater obstacle avoidance for the XLUUV. These projects will help the Royal Navy develop futuristic technologies for XLUUVs for ISR and ASW and testing and validation of these technologies. The 'Manta' XLUUV will be 100ft long and have the capacity to be armed. This means that UK is joining the US in leading world development of full-sized underwater combat drones.[62] The USVs developed by the UK includes 'Guards', 'Black fish' and 'Sentinel'. The Guards are based on the advanced stealth design and water propulsion technology developed by QinetiQ.[63] The British Defence Science and Technology Laboratory have developed a modular USV named "Fenir" in cooperation with the US Army.[64] The German Research Institutes have developed Sentinel which is modular USV equipped with stealth and anti-sinking features. The USVs developed by French Institute and Navies include "Inspectors" like MK1 and Rodell and Sentinel and nearshore attack USVs.

Japan has also developed high-speed USVs like Unmanned Marine Vehicle High Speed (UMV-H), a powerboat hull and works autonomously over a pre-programmed course. UMV-O is an Ocean-type displacement hull equipped with underwater cameras and SONAR equipment. Its applications include bio-geo-chemical monitoring, collection of physical parameters of the ocean and atmosphere. In addition, the latest USV is the OT-91, designed explicitly for maritime intelligence, reconnaissance and mine countermeasures.

Russia has also come up with an AUV named SARMA in 2021, which will have capabilities like lengthy exploration, transportation of cargoes, search operations and maintenance for underwater structures. Another Russian submarine, Belgorod, will carry Poseidon, an autonomous nuclear-powered and nuclear-armed UUV.[65] Russian Navy is trying to match its capabilities with the US and China and has come up with three XLUUVs like Project 7P22 Garmoniya-Guide, Cephalopod Armed AUV and Harpsichord-2P-PM-AUV.[66]

Israel's Elbit Systems has been successfully developing USVs and UUVs in cooperation with Rafael and the Aeronautics Defense Systems. Israel has designed and developed high-speed stealth and highly autonomous systems like Protector, Stingray, Sea Knight, Seagull, Salmon, Silver Marlin and Starfish. These systems are highly modular and are designed on drone technology equipped with modern sensors and weapon systems equipped with unmanned missile systems. These systems can be used for multiple missions like object identification, intelligence gathering, reconnaissance, surveillance, electronic warfare, force protection and mine warfare.

Developments in India

India is also gearing up its UUV capabilities, considering the advancements China and US are making in this sector. The discovery of Chinese autonomous underwater gliders in the Indonesian waters indicates how the UUV technologies are being harnessed for military advantages. Underwater gliders are generally used for gathering data and conducting scientific research, but it is also believed that such data is highly useful for sea-floor mapping to record the course of submarine to go undetected and for anti-submarine warfare.[67] In the past, China has also seized the US underwater vehicle suspected of spying in the South China Sea.[68] India's AUV capabilities include Amogh, Adamya and Maya AUV, which are autonomous in nature and can be used for oceanography, coastal monitoring and mapping of naval mines. Adamya has an endurance of more than 8 hours and can dive up to 1,500 ft. All the three UUVs have been developed by L&T and were showcased at the DefExpo2020. AUV-150 is another AUV developed by Central Mechanical Engineering Research Institute (CMERI) sponsored by the Ministry of Earth Sciences and IIT Kharagpur. It has been built for providing coastal security, mine countermeasures, monitoring and reconnaissance. India has also started to leverage latest technologies like AI for military applications and has formed Defence Artificial Intelligence Council (DAIC) and Defence AI Project Agency (DAIPA) with a Rs 100 crore annual budget specifically for AI-enabled projects.[69] Indian Navy is currently working on 30 AI projects on autonomous systems, maritime domain awareness, perimeter security, decision making, predictive inventory maintenance and management. It is also establishing an AI Centre of Excellence at INS Valsura, in Jamnagar, which would be equipped with a modern laboratory on AI and Big Data Analytics.[70] The Indian navy force development plan includes 200 ships, including nuclear-propelled submarines by 2050. In addition, to boost the 'Self-Reliant India' campaign, the Indian Navy has signed a Rs 13 crore contract to procure indigenously developed Robotic Lifebuoys that will work autonomously for rescue operations in the seas. It is being developed under the Innovations for Defence Excellence (iDEX) challenge that will not only develop prototypes for USVs but also partner with the defence industry towards innovation in the latest technologies like AI, augmented reality, aircraft trainers, underwater domain awareness, drone swarms and data capturing.[71]

Challenges and Possibilities

The sea-based unmanned crafts have emerged to become a significant facet of modern-day naval structures. The rising incidents of cross-border disputes and conflicts across the seas have given rise to enhanced maritime security. The advancements in sensor systems, hull materials, propulsion technologies and data science will be the driving force of sea-based unmanned crafts in future. However, there is still a long way to achieve fully autonomous system developments with an effective man–machine interface with no/limited communication capabilities. The complex, dynamic, and tactical challenges in multi-vehicle operations are barriers to achieving full autonomy. Despite the introduction of the latest technology like AI, swarm intelligence, drone motherships and quantum computing, there are still some areas that require continuous improvements and innovations to match the dynamic environments of the seas. Some of the significant challenges are listed next:

- *Intelligence and Autonomy*: For unmanned systems, achieving the highest level of autonomy is a prime goal which is a high-level conglomerate of complexity, adaptability, capability and flexibility. It requires a trusted, independent and self-governing environment with minimal intervention. In order to achieve this maritime environment, the biggest challenge is preparedness for dynamic and unpredictable situations. Hence, the systems should detect this environment efficiently, identify targets, avoid obstacles and plan autonomously in a seamless fashion. So, effectuation of this intuitive behaviour is one of the most important and formidable goals to achieve and requires constant improvements and innovations in intelligent architecture designs, which in itself is a challenging task.
- *Navigation, Control and Collision Avoidance*: One of the critical technological areas in sea-based unmanned systems is navigation and control. A lot of research breakthrough has happened in this direction, but still, some problems keep appearing with the GPS systems. Some alternative research has been done on CN3 and

terrain mapping, but it needs to be explored extensively. Collision Avoidance is another aspect where sensors and their effectiveness play an important role. Advanced sensors are being used and developed like acoustic sensors, LIDAR, etc. The challenge is with the effective Launch and Recovery Systems (LARS) capable of conducting operations in the sea. Robust command-and-control systems are required to conduct joint operations and to ensure error-free operations of USVs and UUVs over long distances with high endurance capabilities.

- *Swarm Communication and Networking*: The challenge with swarm communication and networking is the secure communication between various unmanned systems in tandem without any external interception to successfully carry out the ISR and other marine warfare operations.
- *Modularity*: The future of littoral warfare is on multi-mission capabilities for which modular and flexible USV and UUV systems are required. Therefore, various companies are designing USVs and UUVs with modular structures equipped with new technologies. The challenge is integrating modular systems with cost-effective host platforms.
- *Data Collection and Analysis*: The amount of heterogeneous data collected from the advanced USVs and UUVs are immense. The secure transfer of this data in a dynamic and real-time environment from one system to another is an area of concern. The transfer of data from a satellite link, underwater stations and swarm systems is a challenging task, and future advancements are expected in this field.[72]
- *Simulation, Visualisation and Testing*: Simulation and visualisation methods have been considered insightful in formulating mission environments at the design stage. However, it requires considerable research and expertise in designing such simulators and extrapolating the exact requirements for the same.
- *Development Cost*: The cost of development and maintenance of USVs and UUVs are very high. In order to reduce the cost of systems, it is essential to integrate technologies and efficiently perform systems integration. Also, the military–civil and academic fusion will open more avenues in the cost-effective development of unmanned systems.

Legal Issues and Policy Considerations

The legal issues pertaining to sea-based unmanned systems or unmanned marine systems are attributed to the status of unmanned systems, maritime zone issues, the role of the United Nations Convention on the Law of the Sea (UNCLOS) and the Law of Armed Conflict (LOAC) issues for weapon release.[73] For sea-based unmanned systems like UUVs and AUVs, the issue is pertaining to its regulatory framework as UNCLOS does not recognise AUVs and there is no distinction between autonomous or remotely operated vehicles. In addition, the definition of a vessel is in terms of navigation and commerce, which have created a regulatory gap for UUVs and AUVs.[74] Apart from these definitional issues of vehicle, vessel and ship for autonomous systems, the other concerns involving these systems are legal and ethical. The ethical issues with these systems are the same as those with autonomous weapons. These systems are used by states for military purposes to carry out ISR activities, anti-submarine operations and for naval warfare. These technologies are expensive and offer navies maritime superiority, but the lack of legal framework poses a significant threat. The risks involved with autonomous technology are unknown and can lead to unintended consequences and escalation of conflicts. Another issue is with the accountability of the autonomous system deployment. According to International Humanitarian Law (IHL), in case where there is no means to identify responsibility for the causalities, such weapons or systems cannot be employed in war.[75]

The US National Geospatial-Intelligence Agency (NGA) provides geospatial intelligence for navigable seaways and aims to provide global maritime geospatial intelligence for national security objectives and joint military operations. However, there is no apparent leader in geospatial intelligence, autonomous technology and security. The legal rules for AUVs are needed to be formed exclusively for their operational use, as the international regulations are not designed in view of unmanned systems. In addition, the legal status of AUVs is still not well-defined.[76]

The lack of policy and doctrine has become a critical issue for the successful deployment of unmanned systems, as the case-by-case use of unmanned systems forms a poor precedent for the future deployment of such systems. Therefore, these issues need to be addressed by the states at the forefront of their maritime development.

Future Considerations and Confrontations

Sea-based unmanned crafts have still a long way ahead and require significant research in areas like Multi-Agent Systems, Swarm Technology and Autonomous AI-controlled USVs and UUVs. The rapid proliferation of these technologies is bringing a global disruption in the economic, military, and social sectors. In addition, the autonomy in the sea will bring significant change in ocean warfare with high endurance attacks and ISR operations. The challenges with these technologies are interoperability issues and subsequent ethical concerns. Also, the dependability and deployability of AI is still an elusive goal to achieve with the kind of risks involved in regulation and the decision-making process.

Furthermore, the lack of common standards and protocols for wireless communication is a concerning factor for underwater communication networks for UUVs. Another issue with the UUV technology is its misuse by the non-state actors and nations to create a next-level conflict by using these systems to attack commercial shipping lines and create asymmetric warfare leading to an exponential impact on the governments and countries globally. UUVs will soon become a formidable strategic and tactical weapon for battlefields. Therefore, India needs to push its gears towards developing sea-based autonomous systems considering its position in the Pacific Ocean.

The development of USVs and UUVs requires standard operation procedures and therefore, it is imperative to devise stringent policies and regulations from organisations, nations and port owners jointly across the globe. Furthermore, direct warfare port scenarios and underwater bases will be an issue of worthy discourse as they will open a pandora's box in ocean warfare. Just to state, the US is developing its underwater charging station for its UUV and China has also shown keen interest in developing an underwater base and a city. It remains to be seen what these advancements will unfold in future and how the dynamics of the countries and the seas will change. The future developments in this domain will rely on communication, energy and autonomy. However, with limited capabilities, a complex environment and immature policies, doctrines and laws will slow down its adoption. Hence, clear policies, doctrines and governance are required to fill this regulatory gap.

Despite these considerations, the maritime environment is not conducive to real-time command, control and communication, therefore the research and development in technologies like AI, data science, swarm technology will drive the future of naval warfare. In addition, the utility of sea-based unmanned systems is boundless, the driving factor is the adoption and deployment of this technology and the regulations and policies that will control naval warfare.

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