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Autonomous Systems in the Underwater Domain: A Limitless Revolution?

Guillaume FURGOLLE

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Executive summary

The prospect of increasing, even massive, use of autonomous systems in all operational segments holds the seeds of a profound transformation of the battlefield. Historically, the underwater environment has been a driver of innovation for autonomous vehicles, due to the complexity of human operations in this environment. The observed increase in civilian activity under the sea over the past twenty-five years has thus led to significant technological advances in the field and a reduction in the cost of commercial underwater vehicles. France can rely on a favorable civil-military institutional, industrial, and scientific ecosystem in this area.

However, it is only in the last ten years or so that technologies enabling a certain level of autonomy for drones—potentially including military tasks—have begun to mature, fueled in particular by the explosion of the aerial drone segment and by the needs of the oil industry, the main historical customer for underwater drones. Autonomy in the underwater environment, however, requires overcoming the physical and technical constraints specific to this environment, such as "roughness" and opacity.

Due to the challenges posed by this highly adverse environment, the development of underwater drones requires the parallel development of several distinct technological components, supported by cutting-edge scientific research. The uneven progress of these different technological building blocks limits the current capabilities of underwater drones, particularly in the areas of communications and endurance.

All of these constraints and limitations continue to weigh on the current ability to deploy fully autonomous operational vehicles in the underwater environment. The sector distinguishes between UUVs (unmanned underwater vehicles), which are underwater vehicles of all types, including remotely piloted or remotely supervised vehicles, and AUVs (autonomous underwater vehicles), which are underwater vehicles that incorporate elements of autonomy. However, technological developments for underwater drones have moved beyond simple automated control to seek greater behavioral autonomy, with the ultimate goal of achieving systems that are fully capable of operating on their own. This transition from automation to autonomy is still in its infancy and will likely rely heavily on artificial intelligence (AI), not only for data detection and analysis, but also for mission autonomy.

Industry remains a driving force for innovation in the underwater drone segment. Most navies around the world have opted for a cautious and iterative approach, testing capabilities based largely on commercial solutions and studying the appropriate integration of underwater drones into their force structure. The military use of autonomous underwater drones in an operational context raises a number of questions, particularly in terms of design choices and safety and security. One of the key questions, however, remains whether underwater drones are intended to provide additional capabilities to naval forces or whether they will offer an alternative to them in certain segments. This naturally raises the question of the operational concept for these autonomous underwater vehicles, for which there seems to be no absolute answer.

Although underwater drones do indeed have the potential, when fully developed, to bring about major disruptions on the naval battlefield, the level of technological maturity for fully autonomous operational applications remains at an embryonic stage today. Certain traditional capability factors could also limit the massive use of this type of vehicle: the cost associated with advanced technology, the need for skilled human resources, and the complexity of operational maintenance. Furthermore, the military ecosystem necessary to fully integrate this type of naval capability does not yet exist.

These issues deserve to be discussed between the armed forces and French industry while these technologies are still in their infancy. This dialogue should be formalized and maintained as technological developments in the sector progress. Given the promise offered by the advent of autonomy in the underwater environment, it seems necessary for navies to invest in and prepare for it, regardless of the concept of use they have chosen, whether offensive or defensive. This involves designing and supporting the integration of the capabilities they have chosen as soon as possible, but also preparing for the potential threat that underwater drones will pose to naval forces and maritime infrastructure.

Résumé

Les perspectives de recours croissant, voire massif, aux systèmes autonomes dans tous les segments opérationnels portent les germes d'une transformation en profondeur du champ de bataille. Or, le milieu sous-marin a historiquement été moteur d'innovation pour les engins autonomes, du fait de la complexité pour l'être humain d'y opérer. L'accroissement constaté de l'activité civile sous la mer ces 25 dernières années a ainsi suscité des progrès technologiques significatifs dans le domaine et une baisse des coûts des véhicules sous-marins commerciaux. La France peut s'appuyer en la matière sur un écosystème civilo-militaire institutionnel, industriel et scientifique favorable.

Ce n'est cependant que depuis une dizaine d'années que les technologies permettant un certain niveau d'autonomie des drones - incluant potentiellement des tâches militaires - arrivent progressivement à maturation, nourries notamment par l'explosion du segment des drones aériens et par les besoins de l'industrie pétrolière, principale cliente historique des drones sous-marins. L'autonomie dans le milieu sous-marin suppose toutefois de pouvoir surmonter les contraintes physiques et techniques spécifiques à ce milieu, telles que la « rugosité » et l'opacité.

En raison des défis posés par ce milieu très adverse, le développement de drones sous-marins nécessite le développement parallèle de plusieurs composants technologiques distincts, appuyé par une recherche scientifique en pointe. Les progrès non homogènes de ces différentes briques technologiques limitent les capacités actuelles des drones sous-marins, notamment dans les domaines des communications et de l'endurance.

L'ensemble de ces contraintes et limitations continue de peser sur la capacité actuelle à déployer des engins opérationnels pleinement autonomes dans le milieu sous-marin. Le secteur fait, à ce titre, la distinction entre les UUV (*Unmanned Underwater Vehicles*), véhicules sous-marins de tous types, notamment télépilotés ou télésupervisés, et les AUV (*Autonomous Underwater Vehicles*), véhicules sous-marins intégrant des éléments d'autonomie. L'orientation des développements technologiques pour les drones sous-marins a toutefois dépassé le simple contrôle automatisé pour rechercher une plus grande autonomie comportementale, l'objectif final étant de parvenir à des systèmes pleinement capables d'opérer seuls. Cette transition de l'automatisation vers l'autonomisation n'en est qu'à ses débuts et s'appuiera vraisemblablement fortement sur les apports de l'intelligence artificielle (IA), au profit de la détection et de l'analyse des données, mais aussi pour l'autonomie de mission.

L'industrie reste aujourd'hui une force d'innovation dans le segment des drones sous-marins. La plupart des marines mondiales ont ainsi opté pour une approche prudente et itérative afin de tester des capacités reposant pour la plupart sur des solutions commerciales et d'étudier la juste intégration de drones sous-marins dans leur structure de forces. Le recours militaire à des drones sous-marins autonomes dans un contexte opérationnel soulève en effet bon nombre de questions, notamment en termes de choix de conception ou sur le plan de la sûreté et de la sécurité. Une des questions centrales reste toutefois de déterminer si les drones sous-marins ont vocation à venir offrir des capacités d'appoint aux forces navales ou s'ils viendront offrir une alternative à ces dernières dans certains segments. Cela pose naturellement la question du concept d'emploi opérationnel pour ces moyens sous-marins autonomes, à laquelle il ne semble pas y avoir de réponse absolue.

Bien que les drones sous-marins soient effectivement susceptibles, à leur plein potentiel, de provoquer des ruptures majeures sur le champ de bataille naval, le niveau de maturité technologique pour des applications opérationnelles pleinement autonomes reste aujourd'hui à un stade embryonnaire. Certains facteurs capacitaires classiques pourraient par ailleurs limiter le recours massif à ce type de vecteurs : le coût lié au caractère technologique avancé, les besoins en ressources humaines qualifiées et la complexité de la maintenance opérationnelle. En outre, l'écosystème militaire nécessaire pour pleinement intégrer ce type de capacités navales n'existe pas encore.

Ces enjeux méritent d'être discutés entre les forces armées et l'industrie française, alors que ces technologies sont encore dans une phase émergente. Ce dialogue devra utilement être formalisé et entretenu au fil des développements technologiques dans le secteur. Au regard des promesses que dessine l'avènement de l'autonomisation dans le milieu sous-marin, il apparaît nécessaire que les marines s'y investissent et s'y préparent, quel que soit le concept d'emploi qu'elles auront retenu, offensif ou défensif. Il s'agit de dessiner au plus tôt et d'accompagner l'intégration des capacités qu'elles auront choisies, mais également de se préparer à la menace potentielle que les drones sous-marins feront peser sur les forces navales et les infrastructures maritimes.

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Introduction

One of the decisive strategic factors in the ongoing Russo-Ukrainian war is the mass use of aerial, maritime, and terrestrial autonomous capabilities, which are transforming the face of the battlefield. Nevertheless, many of these drones are still remotely piloted, operated, or supervised, testifying to the fact that the autonomization of military capabilities is still at an embryonic stage.

Drones are not a novelty in the naval domain. The US Navy's first attempts to use aerial kamikaze drones came during the First World War, when the German armed forces also used remotely operated kamikaze boats against British ships.[1] The US Navy started developing fully operational underwater drones in the 1950s. In recent decades, numerous Western navies have deployed remotely operated underwater vehicles on mine warfare operations, primarily to reduce the risk posed to clearance divers. Ukraine's Magura surface drones,[2] among others, are the worthy modern heirs to over a century of naval engagement with unmanned vehicles.

The underwater domain has historically been a driver of innovation in the field of unmanned vehicles because of the difficulty for human beings to operate underwater at great depth or for prolonged periods. Underwater gliders, the first autonomous underwater vehicles, appeared in the 1990s, and the quest for ever greater autonomization in the underwater domain has continued ever since. But this search has always been constrained by the limitations of the underwater environment: opacity, non-homogeneity, water pressure, and salinity.

Spurred by the wave of enthusiasm around the possibilities opened up by the advent of aerial drones, a prolific and diverse range of naval drones has emerged, particularly underwater drones. This trend is largely being driven by industrial actors, who foresee a potential new revolution comparable to that of the aerial drone industry and have no intention of missing out on market opportunities, even if they have to fund a large part of the development costs themselves.[3]

1. O. Danylov, "Naval Strike Drones: From Ancient Brigands to Modern Times", *Mezha*, August 12, 2023, available at: https://oboronka.mezha.ua.

2. A Ukrainian remotely operated unmanned surface vehicle that exists in several versions (V5 and V7). It was developed by the Main Directorate of Intelligence of the Ministry of Defense of Ukraine (HUR), with the aid of the Ukrainian naval defense industrial and technology base (DTIB) and is exported commercially by the Ukrainian company Spetstechnoexport.

3. L. Lagneau, "Le français Naval Group dévoile le démonstrateur d'un drone sous-marin autonome océanique", *Zone militaire Opex 360*, October 8, 2021, available at: www.opex360.com.

This proliferation of new drones relies on the increasing commercial availability of standardized dual-use components, which have become significantly cheaper: electric motors and batteries, optic and acoustic sensors, and on-board electronics more generally. It also capitalizes on the industry's decades of experience in the development of torpedoes and underwater robots and drones, as well as several advances in the relevant technology sectors. In this regard, these new products are as much original developments as they are aggregates of external standardized components.

How should navies position themselves with regard to this flourishing and increasingly diverse technological offering? Given recent technological developments that herald greater autonomy in the future, how can they make sure not to miss out on the "drone revolution" in the underwater domain?

The answer to this question requires both an intimate understanding of the constraints of the underwater environment and a realistic picture of autonomy in this domain. These are addressed in the first section of this report.

Next, it calls for an interrogation of the contexts in which autonomous underwater vehicles are used during military operations, and the choices that these entail. The second section focuses on these considerations.

Finally, these choices require every navy to define an operational concept that is suited to its autonomous underwater capabilities and to determine how best to integrate the latter into its force structure, which is where any potential revolution will take place. These questions are discussed in the final section.

The long and difficult conquest of autonomy in the underwater domain

Autonomy is defined as the ability of an agent to function or maneuver independently, in other words, without depending on others. More philosophically, it is an agent's ability to figure out, in and by itself, the law governing its thought (its logic) and its action, and to set itself its own norms, as suggested by the Greek etymology of the term (autos, nomos). In industrial parlance, it refers to the time during which a piece of equipment can function without external intervention or energy sources. By extension, in military terms, it determines the distance that can be traveled by a vehicle or a propelled munition such as a missile or torpedo.

A semantic clarification is needed at this point. A drone is an unmanned system that moves and acts either via remote piloting or autonomously. A self-propelled and guided torpedo meets this definition. Nevertheless, a drone is generally understood to be a reusable platform, unlike a torpedo, which is intended as a single-use military effector (a weapon). Although underwater kamikaze drones, like aerial kamikaze drones (one-way attack drones), are increasingly blurring the lines of this semantic distinction, this study does not cover torpedoes.

The desired autonomy for underwater drones, particularly for military applications, must fulfill the following ambitions: They must be deployable far from their bases and operate for long periods of time without external intervention or influence, while being able to adapt their behavior in line with their perception of their environment and react to external events, potentially during an extended mission and based solely on their analysis of the data in their possession.

While this might seem an appealing prospect, in reality, the attempt to develop such drones has been hampered for decades by the very specific characteristics and constraints of the underwater environment. As things stand, the "autonomy" of underwater drones is in practice limited principally to remotely operated or supervised systems.

Civil-military duality: the driver of innovation in the underwater domain

The use of unmanned vehicles in the underwater domain is not new. The first underwater drone appeared in the middle of the twentieth century. In the 1950s, the US Office of Naval Research funded research to develop an underwater drone with a view to exploring the Arctic. This led to the creation by the University of Washington's Applied Physics Laboratory of the Special Purpose Underwater Research Vehicle (SPURV), which was operated remotely via sound waves. The SPURV could dive to 10,000 feet (3,000 meters) and operate for four hours; it had sensors that could measure temperature and conductivity.[4] The University of Washington used the SPURV to collect oceanographic data until 1979.[5]

Following the sinking of the submarine USS Thresher in April 1963, attention turned to developing a platform for deep-sea rescue operations that would overcome the limitations of existing solutions based on diving bells. The development of the technologies subsequently used by underwater drones was therefore largely funded by the US Navy, which also wanted to be able to recover military equipment from the seabed (torpedoes, bombs).[6]

In the 1970s and 1980s, the oil industry used these technologies to develop civilian underwater remotely operated vehicles (ROVs), which are essential for the construction and exploitation of offshore oilfields that are too deep for human divers.[7]

Following a period of stagnation in the second half of the 1980s, technological progress in the ROV industry resumed and accelerated, extending the range of available ROVs and allowing them to carry out more and more underwater tasks, from the simple inspection of structures to the manipulation and installation of objects (sections of pipeline, manifolds, etc.) during the construction and exploitation phases, and particularly for maintenance. The development of very deep-sea oil and gas operations (below 2,000 meters) in the 1990s increasingly encouraged the use of unmanned vehicles. This specificity largely explains the lead taken by Norwegian companies—starting with Kongsberg—given the importance of

4. A measure of water's ability to conduct an electric current.
5. "History of Unmanned Underwater Vehicles", University of Bridgeport, 2022, available at: https://nustem.bridgeport.edu.
6. J. L. Sayer Jr., "CURV Cable-controlled Underwater Recovery Vehicle", 1965, available at: https://cyberneticzoo.com.
7. Gas mixtures enable dives up to 300 m deep in an operational context. Deep-sea diving (below 180 m), known as saturation diving, nevertheless requires divers to decompress for anywhere from a few days to a month.

the North Sea oil sector and the public-private partnership model in Norway (Equinor).[8]

Although the US Navy chose a manned solution for its deep-submergence rescue vehicle (DSRV), other uses were found for unmanned underwater vehicles. Based on a concept dating from the 1960s, underwater gliders using the principle of variable-buoyancy propulsion started to appear in the late 1980s in response to scientific demand for a way to carry out oceanic measurements (temperature, conductivity, fluorescence, and optical and acoustic backscatter).[9] Because the applications for these autonomous underwater vehicles were at that time very specific, their use remained marginal.

The last twenty-five years have seen a sharp rise in activity in the underwater domain, particularly driven by the oil and gas sector and by oceanographic research. This upturn in activity, and so in demand, has led to significant technological advances and prompted the development of ever-cheaper commercial underwater vehicles.[10]

Nevertheless, it was only in the second half of the 2010s that the underwater drone sector underwent a transition comparable to the aerial drone revolution two decades previously, namely the advent of technologies potentially enabling a level of autonomy compatible with complex, even military tasks or missions. This was accompanied by increasing concentration in the corresponding industrial sector. Small and medium-sized firms specializing in underwater drones were acquired by large groups in the defense industrial base, as when General Dynamics acquired Bluefin Robotics in 2016, while mergers were performed to extend coverage of the necessary technological base, as when ECA Group and iXblue were merged to form Exail Technologies in 2022. Beyond industrial considerations, these developments also helped to better meet the state's needs in this area.

The civilian-military duality of technological applications in the unmanned underwater vehicle sector began very early and continues to this day. A dual ecosystem is essential for the accelerated development of the necessary military technologies, as can be seen in the United States or China.[11]

France is fortunate in being able to rely on its own dual military-scientific institutional ecosystem, consisting of the Groupe d'intervention sous la mer (GISMER, Underwater Intervention Group), which is part of the Centre Expert Plongée Humaine et Intervention Sous la MER

8. An oil and wind energy company founded in 1972, the largest company in Norway, and still more than 70% owned by the Norwegian state.

9. J. G. Graver, "Underwater Gliders: Dynamics, Control and Design", Princeton University, May 2005, available at: https://naomi.princeton.edu.

10. A commercial underwater exploration drone can cost a few thousand euros.

11. R. Fedasiuk, "Leviathan Wakes: China's Growing Fleet of Autonomous Undersea Vehicles", Center for International Maritime Security, August 17, 2021, available at: https://cset.georgetown.edu.

(CEPHISMER, Human Diving and Underwater Intervention Expert Center), the Service hydrographique et océanographique de la Marine (SHOM, Naval Hydrographic and Oceanographic Service), and the Institut français de recherche pour l'exploitation de la mer (IFREMER, French Research Institute for Exploitation of the Sea). France exploits this synergy in its Calliope operations, particularly for training French Navy crews to operate underwater drones in demanding operational contexts.[12]

An environment that remains resolutely hostile

Despite significant progress thanks to technological advances in the field, the development of underwater vehicles is still hampered by the intrinsic physical constraints of the underwater environment. These include:

Opacity, both optical and electromagnetic: Water significantly absorbs and diffuses light (visible, infrared, and ultraviolet),[13] impacting optical detection systems but also light-based communications (laser); seawater also significantly absorbs the energy of electromagnetic waves. As a result, only VLF radio waves and electromagnetic waves in the ELF and SLF ranges[14] can penetrate and pass through water, and even then, only a few tens of meters for the former. This theoretically allows submerged objects to communicate with non-submerged objects, but it requires very long antennae (from several kilometers to several thousand kilometers), which are not compatible with small vehicles.

Water pressure and salinity: Because water pressure increases proportionally with depth, underwater vehicles must be built with materials and a structure suitable for the planned use depth; travel speed is limited by water resistance; salinity necessitates the use of corrosion-resistant metal materials; the electrical conductivity of saltwater requires specialized architectures for submerged systems.

Non-homogeneity: The temperature, pressure, and salinity of seawater vary, particularly with depth, and not always in a linear way (stratification, on the surface or at depth); low-frequency sound waves travel very well through water, but not in a straight line (refraction).[15]

Cumulatively, these constraints reduce the overall accessibility of the domain. As limiting factors, they remain as relevant today as they were in the 1960s, despite technological advances.

12. "Objectif: - 6 000 mètres. Préparer les capacités nécessaires à notre ambition", *Cols Bleus, le magazine*, French Ministry of Armed Forces, December 1, 2023, available at: www.defense.gouv.fr.
13. J.-M. Frigerio, *L'Eau à découvert*, Paris: CNRS Éditions, 2015, pp. 74–75.
14. VLF (very low frequency) refers to frequencies between 3 and 30 kHz, while the ELF (extremely low frequency) and SLF (super low frequency) ranges cover frequencies between 3 and 300 Hz.
15. O. Le Calvé, "Le son dans la mer", *Futura*, October 30, 2015, available at: www.futura-sciences.com.

Nevertheless, the underwater domain has always been of military interest for precisely the same reasons: the opacity of the environment and the huge volume of the sea (width combined with depth) make it difficult to detect underwater objects, allowing underwater vehicles to move and operate very discreetly. For that reason, the development of military technologies in the underwater domain has continued steadily since the advent of the submarine.

The need for multi-sector technological development

From the industrial perspective, underwater drones consist of several distinct technological "building blocks": navigation systems, energy source, detection equipment, communication systems, and mission autonomy. Armed or kamikaze drones also include underwater weapons, but this sector is already largely covered by solutions developed for manned naval platforms. The evolution of underwater drones relies on parallel developments in all of these technological areas, developments that have been hampered for decades by the constraints of the underwater domain.

Historically, one of the major limiting factors for the autonomy of underwater vehicles has been underwater navigation. Particular obstacles to the autonomous navigation of underwater platforms include power supply requirements and the general difficulty for communication signals/waveforms to travel through water, not to mention the complexity of interpreting irregularities in the underwater environment and the instability or interruption of signals caused by marine life.[16]

A number of technical developments have nevertheless removed some of the obstacles to UUV navigation:[17] smaller and more effective inertial navigation systems, navigation systems based on magnetometers or Doppler sonar, underwater positioning systems that use fixed acoustic transponders for triangulation, more compact antennae, more effective underwater sensors, and powerful digital information processing tools. New, cutting-edge technological fields are currently the focus of research, capitalizing on advances in AI: terrain-aided navigation and machine learning.[18]

Navigation is, however, still a crucial issue when it comes to developing truly autonomous underwater drones that do not simply follow a programmed trajectory or a regular route, particularly in demanding operational environments. Full autonomy will probably require a combination of different autonomous navigation techniques, as seen in the

16. R. K. Nichols et al., Unmanned Vehicle Systems & Operations: On Air, Sea, Land, self-published, 2020.
17. "Advancements in Autonomous Underwater Vehicle Navigation", PNI Sensor, November 2024, available at: www.pnisensor.com.
18. Ibid.

SLAM approach (simultaneous localization and mapping). This will need a diverse array of sensors as well as on-board capabilities for the fusion and analysis of heterogeneous data.

The energy source to supply the propulsion and on-board systems has also always been a challenge for underwater platforms. A system's endurance and decision-making autonomy and the power of its sensors and effectors are related to the quantity of available energy, which can be generated in situ or stored in advance: The performance of the energy supply system directly determines the military capabilities of the underwater drone.

Energy generation systems developed for submarines, whether aerobic (diesel engine-alternator rectifier), anaerobic (based on anaerobic engines or fuel cells), or nuclear, are hardly suited to small, unmanned underwater platforms, whether because of their bulk or for operational safety reasons. For a small underwater drone, therefore, the available energy density (the ratio between the system's size and the quantity of energy) is a key factor determining how long operations can last without recharging (in dock or on a mother ship).

Russia's Poseidon nuclear torpedo, often likened to a UUV, offers an interesting counterpoint. It is apparently powered and propelled by a liquid metal-cooled reactor,[19] a solution with high specific energy. However, it is reported to be 22 m long, which is well above the standard size for compact underwater drones. Moreover, the reactor was probably designed for short bursts of use for the purpose of delivering a military effect,[20] rather than for long-term operation, as would logically be the case for a large underwater drone.

The solution preferred for underwater drones is currently still battery storage, which effectively limits the platform's endurance. Lithium-ion batteries, which were developed in the 1990s, have high specific energy and have become significantly cheaper since the beginning of the 2000s, representing a substantial and inexpensive energy source for underwater drones, although they are still not quite reliable enough for military use.

As a result, research continues into possible energy sources for underwater drones. In 2023, the US Navy launched a project to develop a hydrogen fuel cell for underwater drones.[21] The hydrogen for these cells is usually stored as a compressed gas in high-pressure bottles (200 to 300 bar), which offer high energy density in relation to weight. This is in line

19. T. Newdick, "Powered Test of Poseidon Nuclear Torpedo, Putin Claims", *The War Zone*, October 29, 2025, available at: www.twz.com.

20. H. I. Sutton, "Russia's New 'Poseidon' Super-Weapon: What You Need To Know", *Naval News*, March 3, 2022, available at: www.navalnews.com.

21. A. Lepigeon, "Un drone sous-marin équipé d'une pile à hydrogène pour développer son autonomie", *Le Marin Ouest-France*, September 18, 2023, available at: https://lemarin.ouest-france.fr.

with a more general trend, particularly for small drones, to return to solutions based on fuel cells, which have the advantage of high energy density despite not being rechargeable or reusable. This is not intended as an exhaustive list, but it is also worth mentioning ongoing research into atomic batteries,[22] a technology that, when mature, could offer a viable solution for underwater autonomy, as well as projects to develop underwater charging stations (on the seabed or submerged).[23]

To summarize, it seems likely that the endurance of underwater drones will continue to rise as energy generation technologies mature.

Detection systems for underwater drones are not breaking new ground. They draw heavily on experience in detection technologies for submarines and ROVs: active or passive sonar, seabed search optical sensors. Current autonomous underwater drones are usually equipped with a combination of different sonar systems that may include side-scan sonar, forward-looking sonar, synthetic-aperture sonar (SAS), or multi-aperture sonar (MAS). The challenge for autonomous underwater drones is more how to use the information they collect and how to classify underwater objects without external intervention. Although object recognition technologies for underwater use still lag behind their terrestrial or aerial counterparts, progress is being made,[24] suggesting that greater autonomy for underwater drones is on the horizon. The other issue for underwater drones, which does not apply to submarines, is that detection systems need to be extremely compact and energy-efficient to enable greater autonomy on a small platform.[25]

Communications are a severe limiting factor underwater. Seawater weakens radio waves and other wireless signals, making the use of broadband or long-range communications unrealistic with current technologies. Moreover, the communication systems used for underwater drones need to be very energy-efficient, which is incompatible with these constraints. Autonomous underwater drones could circumvent this problem by operating without external intervention. Nevertheless, communication systems for AUVs remain essential for military applications. They need to be able to communicate with the rest of the naval ecosystem so that the data they collect can be recovered in real time, exploited, and shared with the rest of the force, and so that they can be

22. F. Terminet, "Bientôt une batterie miniature à énergie atomique?", *Sfen*, January 19, 2024, available at: www.sfen.org.

23. J. Liu, F. Yu, B. He, and C. Guedes Soares, "A Review of Underwater Docking and Charging Technology for Autonomous Vehicles", *Ocean Engineering*, No. 297, April 1, 2024, available at: www.sciencedirect.com.

24. M. Rorvig, "Developing Object Detection Systems for Autonomous Underwater Vehicles", *Mobility Engineering Technology*, October 1, 2021, available at: www.mobilityengineeringtech.com.

25. One example of such a system is the Sonar 76Nano recently unveiled by Thales. It is a synthetic-aperture sonar made up of receive and transmit tiles and was specifically developed for integration into underwater drones.

given new instructions during missions as the operational environment evolves. Communication is also essential for swarming operations.

The inherent opacity of the underwater domain has always posed a challenge for communication, requiring the use of workarounds for recalibrating systems or communicating with the rest of the force. These may involve a link to the surface (via a floating buoy, tethered, surfaced, or dropped), a telescopic mast, or an antenna towed at shallow depth. None of these solutions are particularly suitable for small platforms, however.

Driven by growing civilian and military demand for underwater communications systems, the scientific and technical community is actively exploring new acoustic, optical, magnetic, atomic, and quantum technologies[26] in the hope of improving range, latency, and throughput. It seems likely that progress will accelerate in this area, ultimately enabling the networking of underwater platforms and their integration into a military force structure.

As well as the ability to communicate externally, autonomous underwater drones are also equipped with numerous sensors and systems of various types. Due to their complexity, these drones are rarely developed in their entirety by a single company. They usually incorporate external components with proprietary interfaces and protocols. Ensuring that all these systems can communicate with each other is a challenge in itself. The US Navy has tackled this problem with its Unmanned Maritime Autonomy Architecture (UMMA) initiative,[27] which aims to develop a common, modular, and scalable software architecture for its maritime drones. The North Atlantic Treaty Organization (NATO) is also seeking, via STANAG[28] 4817, to implement a standardized framework enabling interoperability and interfacing between underwater drones by creating blueprints for Command and Control (tasking and reporting) and for the software architectures of the associated equipment. This STANAG was used for Task Force X[29] trials in the Baltic Sea and for NATO's annual REPMUS exercises,[30] during which it was substantially altered and refined.[31] Manufacturers, meanwhile, adhere to existing standards, such as the NMEA

26. Z. Qu and M. Lai, "A Review on Electromagnetic, Acoustic, and New Emerging Technologies for Submarine Communication", *IEEE Access*, No. 12, January 12, 2024, available at: https://ieeexplore.ieee.org.

27. "Unmanned Maritime Autonomy Architecture (UMAA)", AUVSI, March 5, 2025, available at: www.auvsi.org.

28. NATO Standardization Agreement.

29. An initiative piloted by NATO's Allied Command Transformation (ACT) to test a wide range of autonomous systems with a view to accelerating the off-the-shelf acquisition of commercial systems for military purposes, particularly maritime surveillance.

30. Robotic Experimentation and Prototyping using Maritime Uncrewed Systems.

31. "STANAG 4817 Completes NATO's MUS Jigsaw", *Janes*, October 17, 2025, available at: www.janes.com.

norms[32] used widely in the maritime world to regulate communications between marine equipment, including GPS devices, or the Robot Operating System (ROS), an open-source software architecture developed for robot systems in 2007.

Driven by growing or emerging needs for interoperability between all types of underwater drones, the development of communication and information exchange standards is progressing at a rapid pace. Subject to the maturation of other necessary technologies, the prospect of joint underwater operations involving underwater drones seems achievable.

As well as the technological building blocks that directly concern underwater drones, various peripheral systems may also be needed, particularly launching and recovery systems. Individual drones can be launched or recovered from land on an ad hoc basis using existing technologies (cranes, swing jibs, or ramps), but the mass use of underwater drones from land would require suitable, automated infrastructure at launch sites, for example via submerged launch/recovery bays or ramps. Saronic's vision of the shipyard of the future[33] illustrates this reality from a drone manufacturer's perspective, but it is also valuable for users. This type of infrastructure does not currently exist, however.

The launch of underwater drones from ships is also a challenge. The US Navy is currently experimenting with launching underwater drones from its submarines' torpedo tubes.[34] For surface ships, the usual solutions for machine launch and recovery rely on swing jibs or davits, which lack flexibility and are unsuitable for the mass deployment of underwater drones. Technological solutions are starting to appear, such as automated launch and recovery systems on mother ships,[35] but they require structural adaptations to ships and so will be limited to new generations of surface ships. It may even be necessary to build specialized ships just for the deployment of underwater drones.

To summarize, researchers, manufacturers, and navies, motivated by the demand for more autonomous underwater drones and their wide range of potential applications, both in the civilian sphere and for military purposes, are exploring all avenues to gradually overcome these challenges. Some technological sectors are progressing faster than others, however. Full autonomy for underwater drones will require the ability to bring together the entire range of necessary components.

32. Norms defined and regulated by the National Marine Electronics Association, an American non-profit association of marine electronic device manufacturers.
33. "Building the Fleet of Tomorrow", *Saronic*, available at: www.shipyardofthefuture.com.
34. L. Willett, "US Navy Continues AUV – SSN Torpedo-Tube Launch and Recovery Efforts", *Naval News*, October 27, 2025, available at: www.navalnews.com.
35. W. Zhang et al., "An Underwater Docking System Based on UUV and Recovery Mother Ship: Design and Experiment", *Ocean Engineering*, No. 281, August 1, 2023, available at: www.sciencedirect.com.

France is fortunate in having a well-established, multifaceted industrial ecosystem in this area, comprising large naval industrial groups such as Naval Group or Thales, which have expertise in systems integration and naval architecture, specialist actors such as Exail in maritime robotics and navigation systems or ECA Group in robotics and automated systems, and small and medium-sized companies developing solutions involving innovative sensors and on-board AI software, for example. To overcome the challenges around autonomy in the underwater domain, excellent cooperation and industrial synergy between these actors seems essential if France is to position itself as a serious competitor in the field and effectively develop a sovereign national capability commensurate with its military and civilian ambitions.

From automation to autonomy

At the operational level, the desired autonomy for underwater drones combines the ability to operate for long periods of time and at distance without needing to be resupplied (endurance) with the ability to operate independently without external intervention (mission autonomy).

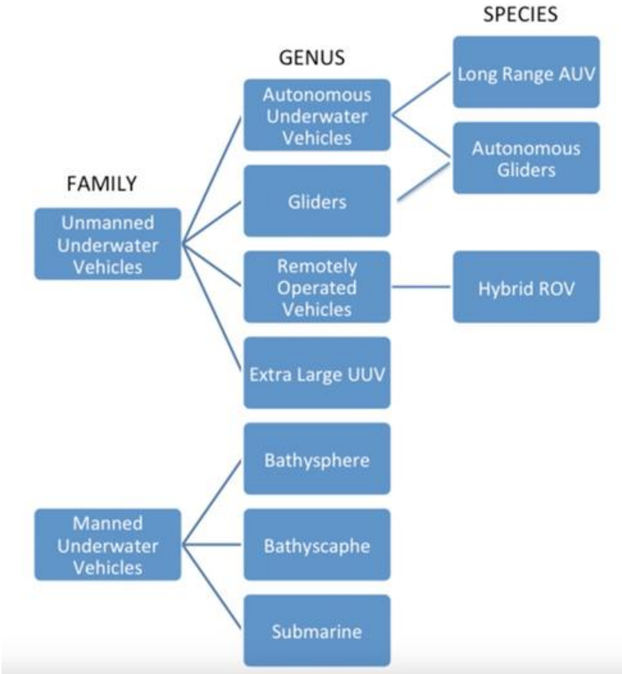
Mission autonomy refers to autonomy in action, in other words the ability of an underwater drone to carry out simple or complex missions without external intervention, whether in the form of additional data or instructions. It requires the drone to be able to apprehend the complexity of its external environment and adapt to it in a flexible way.

This concept of mission autonomy is reflected in the semantic distinction between the two categories of underwater drone:[36]

- **unmanned underwater vehicles (UUVs)** comprise a fairly broad category including remotely operated vehicles (ROVs), which are operated via cable or by acoustic signals, as well as underwater drones capable of navigating autonomously but acting under external supervision;
- **autonomous underwater vehicles (AUVs)** are fully autonomous drones that navigate and maneuver independently and can adapt their behavior to what they perceive in their environment; underwater gliders fall into this category.

36. D. Hume, "Underwater Vehicle Classification", *The Liquid Grid*, March 19, 2019, available at: https://theliquidgrid.com.

Diagram 1: Indicative classification of underwater vehicles[37]



Source: "The Ocean Vehicle Taxonomy", The Liquid Grid*, © David Hume.*

Nevertheless, the minimum autonomy threshold to warrant the label of autonomous underwater drone is subject to debate, and many current AUVs are not actually fully autonomous.

An underwater remotely operated vehicle (ROV) represents the zero level of mission autonomy. An underwater glider carrying out a pre-planned mission, with limited ability to adapt its behavior to its environment, represents an intermediate level. Absolute autonomy would correspond to underwater drones capable of carrying out complex missions, on the same level as a human crew, within a force of autonomous drones operating in synergy.

The level of mission autonomy in the underwater domain has risen in stages. Underwater ROVs laid the groundwork by replacing a human pilot with a cable transmitting orders to the vehicle's active functions. This represents the most basic level of autonomy, as shown in the diagram above.

The first breakthrough enabling greater mission autonomy was the advent of onboard computers capable of performing complex tasks in response to simple instructions and transmitting data about the environment collected by the drone's sensors, although in small quantities due to the low throughput of underwater acoustic communications.

37. Ibid.

Nowadays, a cable connection is no longer needed to transmit motion videos from significant depth. The vehicle's on-board processors can classify targets and locate them by sonar and send this information in short text messages relayed through underwater acoustic communication channels.

Moreover, modern autonomous underwater drones are equipped with sophisticated navigation systems that incorporate route-planning algorithms, as well as motion control technologies that allow them to carry out complex tasks, such as adapting their route in response to environmental data, avoiding obstacles, and using terrain-aided navigation. Nevertheless, autonomous underwater drones remain largely pre-programmed. Their motor functions are automated and react to their environment in line with set parameters. This corresponds to autonomy levels two and three.

In recent years, researchers have sought to move beyond simple automated behavior toward greater mission autonomy. The ultimate goal, capitalizing on the miniaturization of electronic components, the increasing computing power of processors, and the development of AI tools, is to develop fully autonomous drones that can operate without external intervention, optimize their navigation and mission execution on the go, and are integrated into a complex, composite network of sensors and effectors. This is particularly the case in the military sphere.

This still seems like a distant prospect, however. The transition from automation to autonomy in the underwater domain has scarcely begun. Its success will be determined by whether agentic AI lives up to its promise in terms of information fusion and analysis, learning ability, and decision-making capacity in an opaque and complex environment. By contrast, the considerably improved processing power of on-board computers makes it possible to envision specialized[38] unpiloted underwater systems with increasingly effective tactical decision-making capabilities, as seen in next-generation torpedoes like France's F21 Artemis.

38. In the sense of systems designed to perform a clearly defined operational task.

Integrating underwater drones into an operational employment framework

The prospect of acquiring more or less autonomous underwater drones in the short to medium term, thanks to flourishing industrial activity in this area, has prompted navies to focus on the potential military uses of this type of asset or capability. This raises questions around design choices for these platforms, exposure in a naval operational context, and the ecosystem needed to support the capability.

What missions can underwater drones perform?

On top of the fact that the industry has historically driven numerous developments in the underwater drone sector, the potential of autonomization, as seen in the aerial drone revolution, has led many manufacturers to invest in the sector so as not to miss out on the technological shift in the underwater domain and to start developing technological solutions (platforms or equipment). Manufacturers are taking the initiative to spontaneously offer a wide range of products, particularly to state actors.

This situation, as well as the recent maturation of technologies that make the autonomous military use of underwater drones a realistic prospect, has led most navies to favor an iterative approach to integration into their force structures: considering and testing the possibilities offered by industrial solutions and matching them with potential operational uses. That is one of the purposes of the annual REPMUS exercises, which bring together NATO navies and companies in the sector,[39] and of the Dynamic Messenger (DYMS) program, a NATO initiative that provides as realistic an environment as possible for training and testing military equipment.

The US Navy, a pioneer in this field, conceptualized the possible modern uses of underwater drones at an early stage in its Unmanned Undersea Vehicle Master Plan, published in 2000 and updated in

39. "Exercice militaire REPMUS 25: L'OTAN teste ses drones au large du Portugal", *Euronews*, September 29, 2025, available at: https://fr.euronews.com.

November 2004.[40] Still one of the rare formal documents to have addressed the topic, it effectively laid the conceptual groundwork for the sector.

This document lists and describes nine possible missions for underwater drones: intelligence-surveillance-reconnaissance (ISR), mine countermeasures, anti-submarine warfare, inspection/identification of underwater objects, oceanography, communications/navigation network node, payload delivery, information operations, and time critical strikes. These domains are grouped under the four conceptual pillars for maritime operations set out in Sea Power 21, the US Navy's vision for how to adapt to the challenges of the twenty-first century: defensive (Sea Shield), offensive (Sea Strike), sea-based operations (Sea Basing), and connectivity (ForceNet). This list illustrates the very wide range of possible applications for underwater drones in naval operations, at least theoretically, and a possible model for their integration into the components of naval action. Nevertheless, as things stand, the principal military uses for underwater drones remain surveillance of the underwater domain (ISR) and mine countermeasures.

The UUV Master Plan clearly states the core applications for underwater drones: the ability to collect information, both before[41] and during operations, and to engage targets in environments denied to traditional naval forces. In that sense, it makes the most of the operational advantages specific to underwater drones, namely autonomy, persistence, discretion, deployability, adaptability to the operational environment, and reduction of risk to forces.

Technological advances since 2004 have not contradicted this vision of the wide range of possible operational uses for underwater drones and their added value when complementing traditional naval forces in specific use cases. Nevertheless, the question remains of how to best integrate them into a naval and air force structure.

The importance of the size, capabilities, and cost ratio

Because of the environmental constraints discussed in the previous section, any underwater drone is necessarily a compromise. This fact is well illustrated by the acronym SWaP (Size, Weight, and Power), which is widely used in the industrial sector when talking about space systems or drone-based systems. More broadly, it is essential to find a balance between pressure resistance (which determines maximum depth), size and weight (which affect buoyancy, the energy required for propulsion, stealth

40. "The Navy Unmanned Undersea Vehicle (UUV) Master Plan", Defense Technical Information Center, November 9, 2004, available at: https://apps.dtic.mil.

41. Intelligence Preparation of the Battlespace.

capabilities, and payload), and the energy source (which powers propulsion, equipment, and payload and so determines endurance). Finally, the cost factor is also relevant when considering possible mass use.

There is nothing absolute in this balance; any of the parameters can take priority depending on the purpose envisaged for the system. Endurance requires either a lot of energy, or a very economical mode of propulsion and/or a limited payload and sensors. Stealth calls for smaller, more autonomous platforms. Connectivity or multi-sensor information collection need a significant payload. There are two obvious but contradictory solutions: specialized drones, or larger drones.

The 2004 UUV Master Plan divides underwater drones into four classes depending on their displacement:[42] man portable (10 to 50 kg), light weight (around 250 kg), heavy weight (around 1.5 tons), and large (around 10 tons). An underwater glider falls into the portable category, while a REMUS 600 long-endurance detection and identification UUV weighs around 240 kg and is more than 4 m long. These classes reflect the different ways these drones are intended to be operated at sea: torpedo tube for light weight drones, missile launch silo for heavy weight drones, and from a base for large drones.

Diagram 2: Classes of underwater drones

Portable (Micro/Mini/Small UUV) Up to 50 kg Portable – launched from a ship or boat REMUS 100	Light weight (Medium UUV) Around 250 kg Launched from a ship REMUS 600
Heavy weight (Big UUV) Around 1,500 kg Launched from a ship or pier Bluefin-21	Large (LDUUV – XLUUV) 10 tons or more Launched from a pier or a specialized ship Orca

Source: Author's infographic © Ifri, 2026.

Interestingly, while navies prefer off-the-shelf purchases of single-mission (particularly ISR) or consumable underwater drones, state-funded naval underwater drone programs are increasingly focusing on extra-large platforms (XLUUVs) that offer high performance, long endurance, and a baseline level of versatility. Examples include the Ghost Shark, developed by Anduril for the Australian and US navies (3 tons),[43] the British Excalibur

42. In naval architecture, a ship's displacement is defined as the volume of water displaced by the submerged part of the ship, multiplied by the density of seawater. This displacement is directly related to the waterline because, as stated in Archimedes' principle, the buoyant force acting on a body in water is equal to the weight of the water displaced by that body.

43. M. Yeo, "First Ghost Shark Extra Large AUV Delivered to Australian Navy", *Breaking Defense*, November 3, 2025, available at: https://breakingdefense.com.

(19 tons),[44] or the various types of XLUUV developed by the Chinese navy, such as the AJX002 (around 20 m long and over 1 m in diameter), which was unveiled at a military parade last September.[45] Similarly, in 2024, France's Direction générale de l'Armement (DGA) signed a framework agreement with Naval Group for the design, production, and testing of an underwater combat drone demonstrator[46] based on its XLUUV prototype (10 tons).[47]

This does not mean that the entire fleet of military underwater drones will be composed of XLUUVs. On the contrary, they will probably be in the minority. Small or medium-sized underwater drones are perfectly sufficient for specialized tasks like ISR, seabed surveillance, or mine countermeasures, and they are already available commercially at a manageable cost.

Rather, this focus on XLUUVs reflects the important relationship between size and military capabilities, which is even more salient for underwater drones than in other domains. The issue of deployability is another key consideration. Given the current state of energy storage and propulsion technologies, underwater drones generally cruise at a low speed (between 5 and 10 knots) so as to increase their autonomy. For the purpose of responsiveness, there is thus real added value in being able to deploy underwater drones as close as possible to their area of operations, whether from another naval platform or, for drones launched from land and for countries with multiple coastlines, via an air and/or land route. This deployment capability de facto limits their size. With this in mind, a maximum length of 12 m seems realistic. Moreover, launching equipment (cranes, swing jibs, or davits) on non-specialized ships is not designed to handle more than 1 or 2 tons. The required compactness of underwater drones therefore represents a real challenge, forcing navies to make choices about their design and use.

The compromise between cost and risk

Another consideration for the use of underwater drones is the value scale. Aerial drones are usually divided into three value levels: reusable, attritable, and expendable. Although they are not associated with well-defined cost bands, these levels reflect different approaches to use, underpinned by concepts of cost and mass: Low cost enables mass which enables expendability. Drone-delivered munitions and kamikaze drones fall into the expendable

44. J. Hill, "Royal Navy Name Project CETUS XLUUV, 'Excalibur'", *Naval Technology*, May 16, 2025, available at: www.naval-technology.com.
45. "China to Reinforce Naval Pressure over Taiwan Strait with New AJX002 Extra-Large Underwater Drone", *Army Recognition*, September 8, 2025, available at: https://armyrecognition.com.
46. UCUV: Unmanned Combat Underwater Vehicle.
47. "Naval Group réalise les premiers essais de son grand drone sous-marin avec la Marine nationale", *Le Marin Ouest-France*, October 24, 2025, available at: https://lemarin.ouest-france.fr.

category, while ISR drones are classed as attritable. In the underwater domain, the intrinsic hostility of the environment can drastically increase costs for autonomy, autonomization, performance, or reliability. While a commercial underwater glider costs just a few thousand euros, equipping an underwater platform with an explosive charge, a sensor payload, or a more sophisticated autonomy suite poses technological challenges that, while surmountable, would add significantly to the platform's cost compared to existing technological solutions. For example, the cost of a military-grade underwater glider is currently around 250,000 euros. Similarly, the Ukrainian Magura V5 kamikaze surface drone is estimated to cost between 250,000 and 500,000 euros, compared to 100,000 euros for an aerial platform like the Shahed-136/Geran-2. The cost by no means rules out the use of underwater drones as expendable military objects,[48] but it does raise questions about the feasibility of the kind of mass deployment seen in the air domain, especially for mid-size navies. When it comes to their use of underwater drones, navies will have to consider their own value thresholds, and particularly the value at which a platform stops being expendable. Answers will vary depending on each navy's strategic culture.

Moreover, as an extension of the cost question, there is the question of the risk of "loss". This risk covers two scenarios: the risk that an unreliable drone poses a danger to other sea users, and the risk that the drone is captured by an adversary.

In terms of the second scenario, it is much easier to capture an underwater drone than an aerial one. Large, reusable drones will probably be included on states' lists of military ships, but this will not necessarily be the case for smaller drones, and certainly not for expendable drones. As a result, they will not necessarily be clearly marked as belonging to a particular state, an ambiguity that unscrupulous adversaries will be able to exploit. There are precedents for capture: An unmarked but probably Chinese military underwater glider was caught in the nets of Indonesian fishermen in 2021.[49] Although the incident was accidental in that case, drones can be captured deliberately, particularly for the purpose of reverse engineering. For example, the Chinese navy's seizure of an American UUV from right under the nose of an American vessel in 2016[50] probably enabled China to make significant progress in its own plan to develop underwater drones, although the drone in question was returned to the US Navy a few days later. As well as capture, there is a risk that a disabled or malfunctioning drone could be recovered by an adversary, as happened in November 2023, when a Ukrainian Magura V5 stranded on the Crimean

48. By comparison, an American Tomahawk missile costs around 1 million euros.
49. "Fisherman Catches Underwater Drone with Chinese Characteristics", *The Maritime Executive*, January 5, 2021, available at: https://maritime-executive.com.
50. T. Moon Cronk, "Chinese Seize U.S. Navy Underwater Drone in South China Sea", US Department of War, December 16, 2016, available at: www.war.gov.

cost was picked up by Russian forces. There is thus a real risk that sensitive technologies could fall into enemy hands.

As for the risk posed to other sea users, each country's approach to military maritime drones will depend on its culture of maritime security. France, for example, has already regulated the conditions for operating maritime drones:[51] They must be marked, undergo safety inspections by qualified inspection bodies, and only be operated by a trained and certified maritime drone operator. Although these rules apply to the use of civilian drones, it seems likely that the French Navy will adopt them as soon as possible, in line with other regulations in the maritime domain. One of the main advantages of maritime drones is their stealth, which stems from their small size and/or their ability to submerge. They are thus almost imperceptible to other sea users.

Given the possibility of increased or even mass use of underwater drones in the future, and without making assumptions about the evolution of national or international regulations in this area,[52] it is likely that many countries will implement technical measures, on top of autonomous underwater navigation, to prevent disabled drones posing a risk to navigation. Nevertheless, less scrupulous states could disregard these considerations when it comes to their military drones, instead prioritizing performance or cost reduction.

In both scenarios, navies keen to prevent the risk of loss will probably incorporate devices into their military drones to facilitate recovery or self-destruction, further increasing the cost of such platforms.

The critical importance of the deployment ecosystem

At this point, it is worth pointing out that the autonomy of underwater drones may have several other prerequisites beyond simply mastering the technological components of the drone itself.

One of the key factors for mission autonomy in the underwater domain is navigation. Autonomy requires the ability to understand and control the environment. While this is relatively simple for aerial drones operating in a transparent medium, and for naval surface drones operating in two dimensions, it is more difficult for underwater drones, which operate in three dimensions in an opaque medium. As well as information collected in real time by on-board sensors, control of the environment will probably

51. Decree no. 2024-461 of May 22, 2024, establishing the conditions for implementing ordinance no. 2021-1330 of October 13, 2021, concerning the conditions for operating autonomous ships and maritime drones and introducing various provisions relating to professional ships.
52. For example, imposed by the International Maritime Organization, or by the European Union, which introduced regulations for aerial drones in 2019.

require the drone to be provided in advance with reliable data about its underwater area of operation, such as bathymetric maps, maps of underwater currents, or bathythermograph profiles.[53] This information, collected painstakingly and over long periods of time by ships specializing in oceanographic and hydrographic missions, constitutes sensitive military data that states do not necessarily share with each other. The ability to deploy autonomous underwater assets outside a navy's usual area of operation could thus be determined by access to such data, either by direct collection or by exchanging maritime data with allies or partners. This could encourage navies with ambitions to deploy autonomous underwater drones to invest in large-scale data collection capabilities or to orient their strategic partnerships around this type of information exchange.

Another decisive factor relates to the ability of autonomous underwater drones to communicate. As discussed in the first section, the fact that seawater absorbs energy means that long-distance communications require high transmission power, which is not possible with the batteries currently preferred for underwater drones. Given the current state of technology, therefore, communications between military underwater drones and the rest of their naval ecosystem, for example to transmit the results of their operational mission, are limited to short or medium distances.[54] This means using a network of relays in the water. These relays may be underwater hydrophones linked to each other and to the coast by optical fiber, as seems to be the case for some parts of China's Underwater Great Wall,[55] or they may take the form of a mobile network of multiple underwater drones that transmit information from one to the other and eventually to a surface command platform with links to the rest of the fleet. In most cases, the solution will probably involve a combination of the two options. The creation of this kind of underwater communications network is far from simple, however, even in national maritime approaches, and particularly for deployable autonomous drones.

Finally, despite their significant autonomy, the ability of autonomous underwater drones to remain in the water for long periods, for example for underwater surveillance of a strategic area, could depend on the ability to recharge them in situ. This fact is driving research into underwater charging station systems,[56] whether on the seabed or suspended in the water, with all the complexity involved in installing them, possibly connecting them to an electrical grid, maintaining them, and enabling drones to dock automatically underwater.

53. A vertical map of how seawater temperature changes with depth at a given location.

54. Another solution would be a physical underwater connection (docking) between the drone and a data recovery station. Although this is not necessarily simpler from a technical perspective, China may have used it for its Underwater Great Wall.

55. H. I. Sutton, "Good Wind Ears: China's Underwater Great Wall", *Covert Shores*, May 27, 2018, available at: www.hisutton.com.

56. Liu et al., "A Review of Underwater Docking and Charging Technology".

While not intended to be an exhaustive list, these points demonstrate that the ambition to deploy autonomous capabilities in operational contexts in the underwater domain involves more than simply purchasing platforms. It requires in-depth analysis of the elements needed to use them in practice.

Operational concept and integration into the force structure

A variety of approaches to the military use of underwater drones

In this hybrid capability segment, comprising both large-scale state-funded programs and turnkey solutions developed by industrial actors, major navies' approaches to the new capabilities offered by underwater drones seem to be heavily dependent on their strategic culture and equations.

The vision of the US Navy, a historic pioneer in the field of underwater drones, is useful when considering how to integrate these new platforms into the force structure of a top-tier navy. The US Navy's strategic plan, published in July 2022,[57] envisages a hybrid force structure by 2045, including 150 large surface and underwater drones and 350 large manned ships, a ratio of around one third to two thirds. Manned, multi-mission platforms are still seen as the heart of the fleet, with the new capabilities supporting them. The plan envisages expanding the fleet with thousands of small, adaptable, scalable, and attritable drones that will improve detection capabilities and increase the fleet's coverage and persistence, as well as producing kinetic and non-kinetic military effects. This hybrid fleet is suited to the US concept of distributed operations,[58] which aims to increase the fleet's lethality and survivability against an adversary of equivalent strength.

This concept is reflected in the underwater domain by the DASH program, run by the Defense Advanced Research Projects Agency (DARPA), which aims to boost the development of autonomous underwater detection capabilities in order to counter asymmetric underwater threats.[59] It uses a combination of two types of systems, both currently in the prototype phase: deployable, expendable, fixed underwater sonar nodes (TRAPS), which communicate with a surface relay through sound waves, and submarine hunter UUVs (SHARK).

57. "Chief of Naval Operations Navigation Plan 2022", US Navy, July 26, 2022.
58. Concept based on the proliferation, in terms of type and quantity, and distribution of naval effectors in order to increase coverage of the maritime area and increase a fleet's resilience and strike power.
59. "DASH: Distributed Agile Submarine Hunting", Defense Advanced Research Projects Agency, available at: www.darpa.mil.

The Russian Navy, capitalizing on its expertise in submarine building, seems to have opted for autonomous platforms oriented toward deep-water missions and endurance, for scientific as well as military purposes. The Sarma drone is intended for long-term operations under the icecap, with a modular design allowing it to perform a range of tasks including geological exploration, seabed surveys, and maintenance of underwater equipment.[60] The Vityaz-D drone, meanwhile, was designed for deep-sea operations, and in 2020 the Russian Navy was planning to base most of its fleet of military underwater drones on this design.[61] These developments reflect an approach to the use of underwater drones that makes the most of their autonomy, endurance, stealth, and versatility in the underwater domain, and can also support the hybrid strategy characteristic of Russian strategic culture. In parallel, for the last ten or so years, Russia has also been developing platforms that can be deployed from submarines or surface ships, like the Harpsichord, for the purpose of advanced underwater surveillance.[62]

For its part, China is drawing on three decades of investment, research, and civilian-military projects by two institutes, the Shenyang Institute of Automation and Harbin Engineering University, as well as its principal shipbuilding conglomerate, the China Shipbuilding Industry Corporation. All three have acquired real expertise in the field of underwater drones and have developed several series of drones for various purposes, both civilian and military.[63] The Chinese navy, now at the forefront in this area, seems to primarily envisage using autonomous underwater vehicles for specialized mine warfare and mine countermeasures or to inspect and handle underwater cables (repair or destruction),[64] but also for underwater ISR missions or anti-submarine warfare.[65] A Chinese XLUUV revealed in 2023 has torpedo tubes,[66] indicating an offensive capability and purpose involving mines, torpedoes, or even missiles.[67] Like the Russian approach, the increasing size of Chinese XLUUVs—the one just mentioned is over

60. I. S. Bisht, “Russia Developing Extended-Use, Under-Ice Aquatic Drone”, *The Defense Post*, September 24, 2021, available at: https://thedefensepost.com.
61. “Vityaz-D Deep-Sea Autonomous Underwater Vehicle”, *Naval Technology*, September 3, 2020, available at: www.naval-technology.com.
62. H. I. Sutton, “Harpsichord_AUV”, *Covert Shores*, March 30, 2019, available at: www.hisutton.com.
63. R. Fedasiuk, “How China Is Militarizing Autonomous Underwater Vehicle Technology”, *The Maritime Executive*, August 22, 2021, available at: https://maritime-executive.com.
64. R. Neve, “China Shakes the World with a New Drone Capable of Cutting 90% of Global Internet Traffic at 13,123 Feet Below the Sea”, *Evidence Network*, August 30, 2025, available at: https://evidencenetwork.ca.
65. Fedasiuk, “How China Is Militarizing Autonomous Underwater Vehicle Technology”.
66. A. Dangwal, “China Unveils Extra-Large, Heavily Armed Drone Submarine That Can Attack Foreign Warships in Stealth Mode”, *Eurasian Times*, February 23, 2023, available at: www.eurasiantimes.com.
67. H. I. Sutton, “China Reveals Another New Armed XLUUV: UUV-300”, *Covert Shores*, May 9, 2024, available at: www.hisutton.com.

40 m long[68]—reflects a turn toward more versatile or lethal autonomously deployed platforms, rather than capabilities deployed from and in support of a naval force. This seems consistent with China's strategy of fortifying the South China Sea against the submarine threat posed by the US Navy in the event of a major confrontation between these two great powers. These drones are intended to form part of the dual project announced by China in 2015 as the "Underwater Great Wall", a composite ecosystem designed to ensure permanent surveillance of the South China Sea surface and undersea area using both fixed underwater equipment and mobile drone-based equipment.[69]

As for France, the French Navy has adopted a more cautious approach to military underwater drones. First, drawing on decades of experience in the use of ROVs for mine warfare, in 2010 France and the United Kingdom launched the MMCM program[70] under the aegis of OCCAR.[71] It comprises a system of naval drones, including underwater drone capabilities (ROVs and AUVs), to detect and neutralize underwater mines alongside clearance divers. It was announced that the system would be fully operational by the end of 2025.[72] As part of its strategy for controlling the seabed, in 2023, France acquired various deep-water drones (from 3,000 to 6,000 m).[73] At the end of 2024, the DGA also ordered eight large, new-generation underwater drones (AUV-NG) from Thales and Exail, with an option for eight more.[74] These drones will be fully integrated into the Système de lutte anti-mines futur (SLAMF) ecosystem, carrying out mine countermeasures as well as seabed control missions. Finally, in 2024, the DGA reached a framework agreement with Naval Group for the design, production, and testing of a large underwater combat drone demonstrator.[75] The objective was to gauge performance and test the feasibility of this type of platform for anti-submarine warfare, as well as to evaluate its possible use in support of a nuclear-powered oceanic submarine component focusing on nuclear deterrence. At this stage, however, the French Navy has not communicated an intention to procure potentially deployable ISR underwater drones, even though they are widely available on the market and in

68. H. I. Sutton, "China Moves Two Super-Sized 'XXL' Uncrewed Submarines to South China Sea", *Naval News*, September 24, 2025, available at: www.navalnews.com.

69. D. Tsering, "China's 'Undersea Great Wall' Project: Implications", National Maritime Foundation, December 9, 2016.

70. Maritime Mine Counter Measures.

71. Organisation for Joint Armament Cooperation.

72. "La DGA livre le premier drone de surface de guerre des mines à la Marine nationale dans le cadre du programme SLAM-F", Direction générale de l'armement, January 21, 2025, available at: www.defense.gouv.fr.

73. CA É. Lavault, "Maîtrise des fonds marins, la touche française du Seabed Warfare", *Revue maritime*, No. 527, November 2023, available at: www.meretmarine.com.

74. "Commande de huit drones sous-marins autonomes de nouvelle génération dans le cadre du programme SLAM-F auprès des sociétés THALES et EXAIL", Direction générale de l'armement, November 12, 2024, available at: www.defense.gouv.fr.

75. "Naval Group réalise les premiers essais".

demand from other navies seeking to complement their submarine fleets' surveillance capabilities.

Unsurprisingly, the United Kingdom initially adopted an approach similar to that of France. The Defence Drone Strategy published in 2024 by the British Ministry of Defence[76] discusses the use of UUVs for mine detection and ROVs for seabed operations, as well as the integration of AUVs as a back-up capability on Royal Navy frigates. The Royal Navy is also developing UUVs that can be launched and recovered via submarine torpedo tubes as part of Project Scylla.[77] In parallel, since 2022, it has been developing an XLUUV as part of Project Cetus. The resulting experimental platform, which started sea acceptance trials this year, was recently named Excalibur and integrated into the Fleet Experimentation Squadron to continue its testing.[78] The real novelty in the British approach is the goal of creating a hybrid system of permanent, large-scale surveillance systems in the North Atlantic, based on a wide range of autonomous and remotely operated aerial, surface, and underwater drones. This is the objective of the Atlantic Bastion concept unveiled in February 2025,[79] with the submarine component falling under Project Cabot. This concept brings the Royal Navy into line with the American vision of a distributed and connected hybrid fleet with autonomous platforms playing a significant role: "uncrewed wherever possible, crewed only where necessary".[80] This radically new approach is dictated by the current strategic reality for the Royal Navy, which lacks classic naval capabilities and is facing a resurgent Russian submarine threat in the North Atlantic.

As well as the major oceanic navies, many other navies are also interested in underwater drones. Beyond specialized missions like mine countermeasures, the goal is either to acquire a more accessible, essentially defensive substitute for submarines, as in Iran[81] or Indonesia,[82] or to supplement a reduced submarine force so as to increase presence and coverage in the underwater domain, as in the case of Australia's Ghost Shark.[83]

76. "Defence Drone Strategy: The UK's Approach to Defence Uncrewed Systems", Ministry of Defence, February 2024, available at: www.gov.uk.

77. L. Willett, "UK Royal Navy Completes 2nd Trial of SSN UUV Launch-and-Recovery Capability Development", *Naval News*, July 25, 2025, available at: www.navalnews.com.

78. Hill, "Royal Navy Name Project CETUS XLUUV, 'Excalibur'".

79. R. Scott, "UK Sets Out Project CABOT Ambition to Deploy Autonomous ASW Screen in the North Atlantic", *Naval News*, February 18, 2025, available at: www.navalnews.com.

80. "First Sea Lord Sets Very Ambitious Targets for Royal Navy Transformation", *Navy Lookout*, September 9, 2025, available at: www.navylookout.com.

81. H. I. Sutton, "Iranian Nazir-1 XLUUV Submarine Drone", *Covert Shores*, July 11, 2020, available at: www.hisutton.com.

82. F. Malufti, "Indonesia Conducts First Torpedo Test from KSOT Autonomous Submarine", *Naval News*, November 2, 2025, available at: www.navalnews.com.

83. O. Caisley, "Plans for $1.7 Billion Underwater 'Ghost Shark' Drone Fleet Unveiled", *ABC News*, September 10, 2025, available at: www.abc.net.au.

The Deutsche Marine, which is facing serious human resources challenges, falls into the second category: It is aiming for a hybrid format by 2035, with around a third of its order of battle comprised of drone capabilities,[84] in an attempt to increase its combat capabilities without burdening human resources. In the underwater domain, this will be reflected in six large underwater reconnaissance drones alongside six to nine classic U212 submarines.

In both cases, the goal is to complement or replace a submarine fleet rather than to support naval operations conducted by manned platforms.

This diverse range of approaches highlights a key factor for autonomous underwater drones, namely their role within the fleet, especially in fleets with significant hybridity (combination of manned and unmanned platforms). This question, central for all drone capabilities,[85] is particularly pertinent for underwater drones, which have reduced communication capabilities.

It is even more important for autonomous underwater drones: Will they be expected to carry out missions that benefit the fleet but are completely separate from other naval operations, or will they operate autonomously within a naval ecosystem to which they will contribute military effects in real time? The second scenario seems much more ambitious, both in terms of the drones' mission autonomy and their interoperability and communication capabilities, especially over long distances.

Overview of the principal recent military UUV projects

Country	Principal recent military UUV projects	Planned areas of use	Observations
United States	Kingfish (UUV) Knifefish (UUV) AUWS (Various) Shark (UUV) Orca (XLUUV) Snakehead (LUUV) HUGIN Superior (LDUUV)	Submarine surveillance/detection Anti-submarine warfare Anti-ship warfare Seabed surveillance Intelligence/reconnaissance Electronic warfare Mine warfare and mine countermeasures Asymmetric warfare Scientific research	Plans for a hybrid fleet (2/3 – 1/3 hybrid format)
China	Haiyi (Glider UUV) HSU-001 (LUUV)	Scientific research Mine warfare and mine	Underwater Great Wall project

84. É. Tenenbaum and L. Péria-Peigné, "*Zeitenwende:* The Bundeswehr's Paradigm Shift", *Focus stratégique*, No. 116, Ifri, September 2023, pp. 49–50.
85. T. Fried, "The Impact of Drones on the Battlefield: Lessons of the Russia-Ukraine War from a French Perspective", *Hudson Institute*, November 13, 2025, available at: www.hudson.org.

	UUV-300CB (XLUUV) AJX-002 (XXLUUV)	countermeasures Deep-water operations Submarine surveillance/detection Anti-submarine warfare	
Russia	Sarma Vityaz-D Klavesin-2P-PM (LUUV) Poseidon	Submarine surveillance/detection Deep-water operations Seabed surveillance Scientific research Nuclear weapon	The Poseidon nuclear torpedo-drone was recently declared operational
France	MMCM (ROV & AUV) UCUV (XLUUV)	Mine countermeasures Anti-submarine warfare	Seabed control strategy unveiled in 2022
United Kingdom	MMCM (ROV & AUV) Scylla (UUV) Manta (XLUUV glider) Excalibur (XLUUV)	Mine countermeasures Submarine surveillance/detection Anti-submarine warfare	Plans for a fully hybrid fleet Atlantic Bastion project
Germany	MUM (XLUUV mothership)	Deep-water operations Submarine surveillance/detection Anti-submarine warfare Mine countermeasures	Plans for a hybrid fleet (2/3 – 1/3 hybrid format)
Israel	Blue Whale (XLUUV)	Submarine surveillance/detection Anti-submarine warfare Mine countermeasures	
Italy	Blue Whale (XLUUV)	Submarine surveillance/detection Anti-submarine warfare Mine countermeasures	
Norway	HUGIN 1000 (LUUV) HUGIN Endurance (LDUUV)	Submarine surveillance/detection Seabed surveillance Scientific research Mine countermeasures Search and rescue	
Canada	SOLUS-XR (XLUUV)	Submarine surveillance/detection	
Turkey	Deringöz (UUV) STM-500 (LUUV) NETA 300 (UUV)	Submarine surveillance/detection Anti-submarine warfare Mine countermeasures Deep-water operations Intelligence Scientific research	

India	HEAUV (UUV) Make-1 (XLUUV)	Scientific research Mine warfare and mine countermeasures Submarine surveillance/detection Anti-submarine warfare	
Australia	Ghost Shark (XLUUV) Speartooth (LUUV)	Submarine surveillance/detection Anti-submarine warfare	Plans for a hybrid fleet
Japan	OZZ-5 (LUUV) Long Endurance UUV (XLUUV)	Mine countermeasures Submarine surveillance/detection Deep-water operations Scientific research Asymmetric warfare	
Indonesia	KSOT-008 (LUUV) JALAROV S11 (UUV)	Submarine surveillance/detection Anti-submarine warfare Mine countermeasures Asymmetric warfare	
South Korea	ASWUUV (LUUV)	Anti-submarine warfare	
Iran	??? (UUV) Nazir-5 (LUUV)	Submarine surveillance/detection Mine warfare and mine countermeasures Asymmetric warfare	
North Korea	Haeil (UUV)	Nuclear weapon	

Source: Table by author © Ifri, 2026.

The impact on operations at and from the sea

One of the core purposes envisaged for underwater drones is to strengthen underwater military surveillance, which is currently carried out primarily by fixed seabed installations (like Russia's MGK-608M SVER in the Barents Sea),[86] by surface ships towing sonar arrays, and by manned submarines.

Hybrid "fortification" arrangements, whether planned or already in development (like the United Kingdom's Atlantic Bastion project or China's Underwater Great Wall), reflect this trend but remain limited to certain

86. "Sver MGK-608 Stationary Passive Sonar Complex", *Global Security*, available at: www.globalsecurity.org.

geographical areas. While the inclusion of underwater drones in these fortified surveillance systems is likely to make them more effective and so more deterrent, it does not represent a novelty in itself. Similarly, underwater surveillance drones that can be deployed from surface ships and submarines will strengthen the range of anti-submarine warfare assets and increase units' detection capabilities, but again without breaking truly new ground. Moreover, underwater ISR drones will confront the same limitations as other platforms: Active sonar detection is highly energy-intensive, while passive detection primarily works at low frequencies, which require a long antenna to be towed.

By contrast, the ability to deploy, in situ and at short notice, underwater local area denial systems comprising both static seabed sensors (recoverable or expendable) and underwater drones, like DARPA's DASH concept,[87] could be a game changer in that they would significantly increase the complexity of offensive underwater operations in any area of operations. Nevertheless, the coverage of such a system would be directly dependent on the number of sensors deployed. As an example, the detection range of a US TRAPS system is estimated to be around 20 nautical miles for a submarine cruising at 15 knots.[88] It would thus be necessary to deploy around 25 modules to fully cover an area of 200 by 200 nautical miles. The US Navy is currently planning to acquire around 50 units. The operational reality of this capability will probably be linked to the ability to acquire its component parts in large numbers, and so at a reduced unit cost.

As for effectors, drone-based underwater weapons are already a reality, whether autonomously operated[89] or fired from a submarine or an XLUUV, like Anduril's Copperhead.[90] Conceptually, however, such weapons are merely evolutions of the torpedo that incorporate recent advances in endurance and autonomy in the underwater domain. They do not require naval forces to fundamentally alter their tactics for protecting against the submarine threat, even though the ability of autonomous underwater drones to attack their targets from below will force adaptations to traditional submarine defense systems and require the development of new assets to handle this type of threat.

Nevertheless, their increased autonomy could potentially give them the ability to "wait" stealthily for targets in a maritime area (the loitering munition concept). This would require a rethink of the conventional view of the submarine threat, which is oriented around the platform-weapon duo, and

87. Ibid.

88. B. Clark, S. Cropsey, and T. A. Walton, "Sustaining the Undersea Advantage: Transforming Anti-Submarine Warfare Using Autonomous Systems", *Hudson Institute*, September 10, 2020, p. 53.

89. H. I. Sutton, "World Survey of Underwater Attack Drones (OWA-AUVs)", *Covert Shores*, January 3, 2024, available at: www.hisutton.com.

90. J. Trevithick, "Copperhead Torpedo-Like Underwater Kamikaze Drones Rolled Out by Anduril", *The War Zone*, April 7, 2025, available at: www.twz.com.

pose a latent threat throughout an area of operations.[91] This threat could affect warships, but also merchant vessels in the event of a trade war. It would be particularly dangerous in coastal regions, where it is notoriously more difficult to detect underwater objects because of the generally higher level of ambient noise. In any case, it will certainly shake up traditional, resolutely offensive models of anti-submarine warfare, which are based on the fundamental dogmas of hunting enemy submarines and restricting their kinematics.

As for submarines operating in the open ocean, and particularly SSBNs,[92] the reality of the threat posed by armed autonomous drones remains to be seen. It will be heavily dependent on the ability of drones' on-board sensors to detect and then engage a very stealthy and silent modern underwater platform within the vast area of the ocean. This seems like a long-term possibility for state-of-the-art XLAUVs or XLUUVs. Moreover, increasing autonomy will make it possible to deliver weapons at long distances without necessarily needing to expose the weapons carrier near the coastline, potentially allowing stealth attacks against an adversary's maritime infrastructure (naval bases and civilian ports). This could take the form of kamikaze attacks, like the recent Ukrainian strike on a Russian submarine in Novorossiysk port on December 15, 2025,[93] or stealthy, close-range, offensive mining, or even neutralization of the conventional systems for protecting such infrastructure (using entangling nets). It also seems fairly easy to turn these attacks into saturation attacks by using swarms of kamikaze drones.[94] In the long term, this might require a reconsideration of maritime defenses for critical maritime infrastructures, which are often located in dual-use port areas (like Brest or Toulon, in France).

The Russian nuclear torpedo Poseidon is a unique case because it is a strategic, supposedly unstoppable nuclear weapon that can also generate devastating conventional effects on coastal installations, according to the Russian authorities. North Korea claimed in 2023 that it had also developed and tested a similar weapon.[95] At this stage, however, the efficacy of this type of weapon remains to be proven.

The innovation sparked by advances in autonomy also raises the possibility of new types of cross-domain weapons that could potentially be highly disruptive, whether in the form of aerial drones deployed in the aerobic phase by an underwater cross-domain platform (like the United States' UGM-84 missile capsule) or drones natively designed to operate in

91. For example, the TLK-150 family of UUVs developed by the Ukrainian company Toloka.
92. Nuclear-powered ballistic missile submarine with second-strike capability, known in French as SNLE.
93. Probably carried out by a submerged kamikaze drone, a more advanced version of the Ukrainian surface kamikaze drone Sea Baby.
94. S. Crowe, "Aquabotix SwarmDiver: A Micro Drone for Ocean Swarming", *The Robot Report*, April 10, 2018, available at: www.therobotreport.com.
95. "North Korea Tests Nuclear Capable Underwater Drone Haeil-2", *Army Recognition*, April 11, 2023, available at: www.armyrecognition.com.

the air or the water, like China's Feiyi drone.[96] These weapons' underwater delivery systems could remain undetected in the water or be launched stealthily from a submarine, posing an aerial threat in close proximity to a naval force and enabling saturation attacks without warning, in contrast to aerial attacks. Although the necessary technologies are still in the development phase, the Chinese example demonstrates the military advantages of this type of capability.

Moreover, the advent of drone-based underwater weapons could potentially add a layer of complexity to A2/AD defensive systems.[97] The ability to deploy underwater loitering munitions, as discussed above, or underwater containerized weapon systems, like the Greek company Delian's Interceptigon,[98] will effectively add a third dimension to the threat facing a naval force operating in denied environments in maritime approaches, probably with a very short interval between detection and impact.

Finally, while the presumed or confirmed sabotage of underwater cables or energy infrastructures is on the rise, it is still primarily carried out by either highly specialized capabilities (deep-sea submarines, military divers…), or rudimentary methods (anchor dragging, for example). The emergence of underwater drones capable of carrying out major operations on an adversary's critical infrastructure, potentially autonomously, will add another dimension to this threat, whether below the threshold or not, and by the same token to our societies' vulnerability and resilience to this type of destabilizing maneuver.

To summarize, while some observers believe that the capabilities discussed above have the potential to fundamentally transform naval strategy, the majority are still at the embryonic stage and have yet to prove their value, particularly in terms of accessibility (in the sense of the cost/operational effect ratio). These potential disruptors must not be ignored, however, and it is essential to keep a close eye on the associated technological developments so as to remain prepared. This is especially the case for the potential emergence of an asymmetric underwater threat, which does not currently exist.

Moreover, beyond the operational capabilities and real autonomy of these systems, we should not ignore the strategic impacts of their potential capabilities. Their accessibility (in the sense of being available in large numbers at low cost, as is the case for aerial drones) and the potential future threat posed by underwater drone-based systems to naval operations or critical off- or onshore infrastructures are factors that must be considered. Solutions to

96. "China Develops World's First Underwater and Aerial Drone", *Defense Mirror*, January 23, 2025, available at: https://defensemirror.com.

97. A2/AD: anti-access/area denial. See J.-C. Turret, "Stratégies de défense par interdiction en milieu sous-marin: Du concept à la réalité", *Revue Défense Nationale*, No. 885, 2025, pp. 145–57.

98. "Interceptigon Drones by Greece's Delian Signal Shift Toward Autonomous Coastal Defense at DEFEA 2025", *Army Recognition*, May 6, 2025, available at: www.armyrecognition.com.

counter this threat will have to be developed and acquired. Moreover, as shown by the Poseidon torpedo, whose military efficacy remains to be proven, the opacity of the underwater domain could allow navies to claim, for the purpose of strategic signaling or intimidation, to have developed a game-changing, low-cost military capability. At a time of increasing conflictuality, especially at sea, it seems likely that more and more navies will turn to underwater drone-based systems to deter potential or known adversaries. As a result, underwater drone-based capabilities are likely to have a significant impact on the naval strategic equation in the future.

Limitations on the massive use of underwater autonomy

The prospects of autonomy in the underwater domain seem unlimited at this point. Nevertheless, navies' ability to engage in this sector on a large scale will be constrained by several factors.

Beyond the technological cost of autonomy in the underwater domain, which is significantly higher than in the air or land domains, as discussed in the second section, the massive use of drone-based assets raises several questions.

The first is the human resources cost of implementing these autonomous platforms. While the use of drone-based systems may initially be seen as a way to develop capabilities at lower financial and human cost, the United States' experience of aerial drones shows that fully exploiting the potential of drones carries a high "human resources cost", especially in hostile operational environments.[99] As well as operators for remotely operated systems, deploying a fleet of drones requires maintenance and logistical staff, mission planners, and analysts to interpret the data collected.

The Russian and Ukrainian experiences in the ongoing war in Ukraine also highlight the impact of the massive use of drones on military human resources, both in terms of the force structure and the development and maintenance of the skills to operate these systems in a context of rapid technological evolution.[100]

Beyond the simple quantity of personnel required, the question also arises of the skills of those responsible for deploying these underwater drones. Navies will need skills for planning missions, interpreting data, and performing in situ maintenance on these complex and versatile or specialized but diverse underwater drones. This is especially true for drones designed to be deployed from naval units, which will require these skills to

99. J. Watling, "Automation Does Not Lead to Leaner Land Forces", *War on the Rocks*, February 7, 2024, available at: https://warontherocks.com.
100. T. Fried, "The Impact of Drones on the Battlefield", op. cit.

be integrated into naval crews either natively or in the form of specialized, deployable teams. With the continuous technological development of naval platforms increasingly calling into question the traditional skills pyramid for naval crews, the integration of autonomous platforms will further complicate the equation, which is already complex for optimized crews. It will also create recruitment challenges in terms of the ability to attract people willing to specialize in this technological path and capable of developing and to retain those skills. This is already a major consideration in the US naval sphere given the possibility of a hybrid fleet within the next ten or twenty years.[101]

The British Project Cabot exemplifies this problem. Conscious of its inability to deploy an ambitious system of autonomous systems in the near term, the Royal Navy is planning the project in two phases. Phase 1, named Atlantic Net, consists of the deployment by a manufacturer, in the form of a paid service,[102] of autonomous underwater data collection platforms under state supervision,[103] with data interpretation and analysis remaining the responsibility of the Royal Navy. This highlights the potentially crucial role of industrial excellence in the deployment of complex, highly adaptable and scalable autonomous platforms. It also reflects an emerging trend of armed forces increasingly needing to rely on private companies to implement complex digital tools that can process massive amounts of data.[104]

The second question around the use of autonomous systems in the underwater domain is sustainment. As discussed in the first section, autonomy in the underwater domain relies on multiple technological building blocks. Moreover, the underwater domain is inherently hostile to technological systems (corrosion, pressure, electrical conductivity, temperature variations…). As a result, maintaining underwater drones in operational condition is likely to be a complicated task.

Currently, most new companies offering autonomous solutions are focusing on production, in some cases mass production, and are developing their industrial infrastructure accordingly. As it stands, there is no logistical ecosystem (sustainment infrastructure, spare parts storage, deployable technical maintenance teams) to support the use of autonomous underwater platforms deployed far from the mainland and operated from deployed units or advanced bases. This is partly due to a conceptual model of mass that sees the drone as an object to be replaced, rather than repaired. Again, however, the expendable nature of underwater drones

101. S. Savitz and A. Perez, "Could the U.S. Navy Fleet of the Mid-21st Century Include Large Uncrewed Vehicles?", *RAND*, January 8, 2025, available at: www.rand.org.
102. Known as the Contractor Owned, Contractor Operated, Naval Oversight model (COCONO).
103. L. Willett, "UK Takes First Acquisition Steps for Atlantic Net ASW ISR Capability", *Naval News*, October 22, 2025, available at: www.navalnews.com.
104. E. Bienvenue et al., "Private Tech Companies, the State, and the New Character of War", Carnegie Endowment for International Peace, December 1, 2025.

remains subject to debate, and it will be highly dependent on the unit cost of each class of AUV and UUV. It seems likely that a majority of underwater drones will be designed to be reusable and so will require repairs. Mass could circumvent this difficulty by increasing the number of platforms on site to compensate for any damage. Everything will depend, once again, on the unit cost of these drones, as well as their size: Non-specialized naval units (in other words, anything except a drone-carrier)[105] will not necessarily have room on board for a significant number of large underwater drones.

After several decades of development in the field, the US Navy, which is firmly committed to the mass acquisition of all kinds of autonomous systems as part of its dedicated Replicator program,[106] is increasingly becoming aware of this issue.[107]

Finally, as for the rest of the drone-based military capabilities sector, there is the urgent question of how to scale up industrial production. The multi-technological nature of underwater drones, particularly the most sophisticated, will probably limit the ability to mass-produce them, while the constraints of the underwater environment will complicate sustainment, especially if they are used intensively. The ability to endure and absorb attrition in this capability sector in the event of a high-intensity conflict will remain a key challenge for the naval defense industrial and technology base.

Moreover, when it comes to the appropriate integration of autonomous systems, whether underwater or surface platforms, into naval force structures, it is not enough to simply acquire such systems. Issues such as the human resources model, sustainment, and regeneration capacity must be taken into account to ensure added value and reliability, without which mass alone does not equate to operational capability. Armed forces and industrial actors should discuss these questions while technological developments in the field of autonomous underwater systems are still in the early stages.

105. Such as Turkey's TCG Anadolu, for example.
106. N. Robertson, "Pentagon Unveils 'Replicator' Drone Program to Compete with China", *Defense News*, August 28, 2023, available at: www.defensenews.com.
107. N. Johnson, "Replicator 3 Should Be the Sustainment Revolution", *War on the Rocks*, November 18, 2025, available at: https://warontherocks.com.

Conclusion

Technological developments in the field of underwater autonomy could open the door to a very wide range of operational uses for underwater drones. Betting on the likelihood of a new capability revolution like that of the aerial drone industry, defense manufacturers around the world are pouring into the naval drone sector so as not to miss this new shift or the opportunities offered by a market that is seen as extremely promising.

As for navies, the majority have launched trials or projects in the field, capitalizing on their own operational experience. Nevertheless, many have opted for a cautious, iterative approach, relying on existing commercially available solutions to tap into the sector's rapid technological progress, driven by industry and science, while limiting their risk in terms of weapons programs. While the lifespan of a modern weapons program ranges from forty to fifty years for a naval asset (ten to fifteen years for development and thirty to forty years of service), technological acceleration and rapid evolution in the drone sector limit the lifespan of a drone to around fifteen years. For the navies currently most active in this sector (United States, China, Russia, United Kingdom, Australia, Iran…), underwater drones are seen as an accessible capability solution, both in terms of cost and time frame, for responding to immediate naval strategic challenges posed by known adversaries.

The mass use of drone-based platforms could form part of a strategy prioritizing total reliance on whichever effector seems to be the most cost-effective and can be used with large numbers of platforms to generate saturation, like Russia's strategy in the Russo-Ukrainian war, or part of an approach dictated by necessity in the absence of alternative ways to achieve the desired operational capability, like the United Kingdom's Project Cabot or Ukraine's naval drones.

The likely cost-of-ownership scale for underwater drones raises doubts about whether navies have the capacity at this stage, in terms of budget, human resources, or structure, to mass-deploy this type of autonomous asset in one or several capability sectors without having to make cuts elsewhere, which would have long-term consequences for the force structure. This is true even for the all-powerful US Navy. Indeed, the example of the Royal Navy's Fleet Air Arm shows that it takes a decade or two to rebuild a lost operational capability across the entire DOTMLPF capability spectrum.[108] For that reason, most navies remain cautious and agree that it is the employment concept for this type of naval asset that should guide technological developments, rather than the other way around.

Many of the XLUUVs unveiled so far are still in the demonstrator or initial testing phase. Their real capabilities remain unproven, particularly in a fully operational context, and will probably depend on further technological developments in the key capabilities discussed in the second section.

Beyond technology, other factors relevant for the integration of drone-based underwater assets into naval forces, such as employment concepts, structural adaptation to human resources, and the development of operational and logistics support ecosystems, are still at an embryonic stage, at best. Admiral Gilday himself, former chief of naval operations in the US Navy, stated in 2022 that the changes required to enable the maximalist vision of a hybrid fleet outlined in the CNO Navigation Plan 2022 would take at least twenty years in the United States, largely because of the networking and multi-platform connectivity challenges inherent in distributed operations, but also because of the investment needed from the American naval DITB to produce these new capabilities.

Moreover, the transition from a fleet of conventional ships to a hybrid fleet including a substantial number of autonomous platforms constitutes a revolution, and its success will be contingent on a gradual approach supported by much experimentation and learning from experience, as demonstrated by naval revolutions in previous centuries.

As a result, although it has the potential to bring about a revolution, the exact details of which mostly remain to be determined, autonomy in the underwater domain does not yet seem to be sufficiently advanced to call into question the value of manned systems. Several countries, including Australia and Brazil, but also potentially Japan or even South Korea, are launching projects to build nuclear submarines for the first time, showing that the manned nuclear submarine remains more than ever a key element in the underwater order of battle for a top-tier navy.

Nevertheless, the very possibility of this revolution means that militaries cannot afford to ignore it. We can offer a number of recommendations so that France does not fall behind in this capability sector.

108. Acronym describing the components of a military operational capability: Doctrine, Organization, Training, Material, Leadership and education, Personnel, Facilities.

1. First, in the spirit of American initiatives like the Navy Unmanned Acquisition Office,[109] France must **capitalize on and bring together its existing ternary ecosystem** in the underwater domain (French Navy – scientists – industry), for example by creating a dedicated civilian-military expert body that would serve as both a center for expertise and intelligence and an experimental facility. The idea would be to guide French research and technological progress in the domain, to have access to comprehensive expertise to monitor foreign developments, to align France's industrial activity with capability needs, to properly understand and help to shape the logistics ecosystem needed to implement these assets, and to develop, over time, the military skills required for implementing these complex systems.

2. **Move beyond the seabed control strategy and develop a first national operational concept** for this range of specific capabilities that is consistent with the capabilities required for the French Navy's current and future missions and operational scenarios, in order to:

   - orient the design choices of French manufacturers and guide them toward solutions that meet national needs, rather than exclusivelyproducts intended for the export market;
   - determine the required and appropriate effort at the capability level for acquiring the necessary capabilities within the timeframe in which they are likely to be available.

   This first employment concept could be revised in due course to incorporate feedback from experiments and to take into account technological developments with strong operational employment prospects.

3. **Consider the potential threat represented by capabilities related to autonomous underwater drones** in the event that they are acquired by strategic competitors, and define strategies to counter it if necessary by identifying the necessary capabilities. Determine the required timeframe to acquire these capabilities.

4. **Start laying the groundwork for the eventual integration of the acquired capabilities into the force** in terms of logistics support, skills development, and the adaptation of launch infrastructure, both in dock and on naval units.

109. S. Lagrone, "New Navy Unmanned Acquisition Office Could Oversee up to 66 Programs, Consolidate 6 PEOs", *US Naval Institute News*, November 18, 2025, available at: https://news.usni.org.

- Given the foreseeable costs of developing autonomous underwater drones and their associated ecosystem, as well as the technological challenges of operationalizing this capability, **start exploring potential synergies with strategic partners whose vision for the operational employment of these assets is compatible with that of the French Navy.** For underwater drones deployed by naval assets, these could be partners that deploy naval forces in comparable formats (Italy, India, United Kingdom, even Brazil…). For the defensive component (underwater surveillance of approaches, protection of critical underwater infrastructure), the list of potential partners includes all partner countries with a coastline facing the open sea, with operational expectations likely to be more widely shared. In any case, the **connections with alliances or strategic partnerships and questions of interoperability must be considered in advance**, because the strategic value of drone-based underwater capabilities will probably depend in part on their ability to be integrated in the future into broader multinational, multi-domain, hybrid, and multi-platform systems.

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