drones

Review

Autonomous Underwater Glider: A Comprehensive Review

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Abstract: A comprehensive review of Autonomous Underwater Gliders encompasses their development, technological advancements, operational principles, and applications in various fields. It explores the different types of architectures, such as those with blended wing or conventional designs, and examines their roles in scientific research and civil use. The review also addresses the challenges and limitations in areas like payload, navigation, swarm management, and the effects of underwater environments on glider performance. This knowledge is essential for improving glider technology and expanding their potential in future underwater exploration and data collection missions.

Keywords: AUV; sub; autonomous; underwater; glider; review

1. Introduction

A sub glider (SG or sub glider), also known as an Autonomous Underwater Glider (AUG), is a vehicle designed to glide through the water in a manner like the flight of a bird: for many years now, vehicles like these have been used for various oceanographic research and environmental monitoring applications, as well as for commercial purposes such as offshore oil and gas exploration. From an architectural point of view, the AUGs are typically equipped with wings (or hydrofoils) that generate lift as they move through the water (both in the immersion phase and in the emerging phase from the water), allowing them to achieve forward motion with minimal energy consumption. The vehicle uses a buoyancy-driven propulsion system, which involves adjusting its internal buoyancy to control its vertical position in the water column: by alternately adjusting their buoyancy and angle of attack, sub gliders can glide up and down through the water, covering large distances while consuming very little power.

From a payload perspective, the SGs are equipped with a variety of sensors and instruments to collect data on oceanographic parameters such as temperature, salinity, pressure, currents, and biological activity. They are also capable of operating autonomously for extended periods, often weeks or even months, without the need for human intervention, so they become valuable tools for long-term ocean monitoring and research missions, as well as for collecting data in remote or inaccessible areas of the ocean.

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2. Underwater Glider

Underwater gliders are designed for long-duration missions. They use changes in buoyancy and hydrodynamic lift to glide through the water, making them energy-efficient and capable of covering large distances over extended periods. An excellent and comprehensive general introduction to underwater gliders can be found in the work of R. Bachmayer et al. [1]; there are also some examples of architecture and real use, this in order to enter into the discussion of the subject by providing real case studies.

2.1. Generalities

The core component of an underwater glider is the buoyancy engine, which adjusts the vehicle's buoyancy by changing its volume; this is typically conducted by pumping oil or another fluid between an internal tank and external bladders. When the glider wants to dive, it increases its volume by pumping fluid into an external bladder, decreasing its density; to ascend, the fluid is pumped back into the internal bladder, increasing its density.

For the pitch setting (and the correlated angle of attack, or AoA), it is necessary to move the battery pack or a ballast (and therefore the center of gravity, or CG) forward or backward. However, to control the heading (direction), it is necessary to tilt the pack or the ballast at a certain angle.

To reduce the force required to actuate the oil piston, which pushes the oil in the bladder at high depth, it is necessary to reduce the piston surface (diameter) and increase the stroke. So, the buoyancy engine resembles a "shotgun." The vehicle is equipped with wings that generate lift to move forward: the AoA of the wings, combined with the forward motion generated by gravity (during descent) or buoyancy (during ascent), creates the gliding motion, so by alternating between descending and ascending, the glider follows a sawtooth pattern through the water, using minimal energy to traverse significant distances.

Internal moving masses, such as batteries or ballast, are shifted to control the pitch (nose-up or nose-down angle) and roll (rotation around the longitudinal axis) of the glider; this allows the glider to adjust its glide angle and direction. A rudder or internal gyroscope or a quick movement of a battery pack (or ballast) can be used to control the heading of the glider, enabling it to follow predetermined paths or respond to navigation commands.

Pros and Cons of the Glider Architecture

Underwater gliders are versatile and efficient tools for marine research and monitoring. Their unique propulsion method, based on buoyancy changes and hydrodynamic lift, allows them to operate for extended periods with minimal energy consumption. While they have some limitations, their advantages make them invaluable for a wide range of oceanographic and environmental applications. The main mission profiles and the related employment strategies are optimized, according to the dedicated environment, and are examined in [2] detail: three types of typical missions (pure drift, corrected drift, and glider) and finally a hybrid one (Jellyfish).

Let us now examine in detail the strong and the most critical points of this type of underwater vehicle: this step is necessary because we will examine in the continuation of the work the most notable issues.

The pros are as follows:

- It is possible to plan long-duration missions with a very considerable range.
- The vehicle has extremely quiet navigation.
- The energy consumption for the motion is extremely low and is concentrated in the moments in which the vertical direction is changed.
- Human operator supervision is minimal (*launch-and-forget* mission).
- Reduced need for constant human supervision.
- The vehicle can collect high-resolution, long-term data, ideal for a scientific research campaign on the high seas.
- It is possible to manage a small group of similar vehicles and have them act as a coordinated swarm.
- Since there are very few moving components, the vehicle has a very high intrinsic reliability.
- Its architecture allows it to reach extremely high depths.

The cons are as follows:

- The vehicle is much slower than a normal propeller-driven AUV, and its dynamics and, obviously, its ability to respond to motion disturbances are rather reduced (although it remains effective).
- Although it can be suspended at a certain depth (hovering), it is unable to change attitude unless it starts moving.
- To reduce the internal volume and therefore the space to be allocated to the payload.
- To keep the vehicle agile and fast or to reach extremely high depths, it is necessary to reduce its total internal volume; this leads to a natural restriction of the payload.
- Note that by scaling up the vehicle to have the same buoyancy forces, it is necessary to also enlarge the oil bladder accordingly.

We would like to point out a very interesting review by David Meyer: extremely precise and timely, it proposes a series of applications and configurations to schematize and order the use of SGs for ocean exploration [3].

2.2. Evolution of the Vehicle

The concept of an underwater glider comes from afar and was born from the development of drifting buoys for ocean research that were placed in ocean currents (Gulf Stream, Humboldt, etc.) to evaluate their speed and physical characteristics such as temperature and salinity. The first step was to vary the buoyancy to immerse the vehicle and stabilize it at a certain depth; the second was to exploit the vertical motion and transform it into a translational motion. From here, a continuous refinement of technologies and hydrodynamic solutions.

2.2.1. The Beginning: ALACE

From the technological point of view, it all goes back to the vehicle that was part of the ALACE (Autonomous Lagrangian Circulation Explorer) project [4–6]. It was nothing more than a cylindrical buoy (see Figure 1) that had the ability to vary its buoyancy and thus its depth; otherwise, it simply drifted, as it had no ability to be able to vary direction or speed. The buoy was a simple cylinder, but inside it had all the subsystems that we would later find in more sophisticated vehicles, i.e., the expansion bladder to control buoyancy and to conserve depth, the satellite linkage system and the omnidirectional beacon overhead, and the battery pack that also provided a modest payload. After this campaign, the need for a higher-performance vehicle was felt. The cited papers are interesting because they devote a very thorough section to vehicle mission reliability: this aspect of the study is critical because these vehicles are rather autonomous, and their environment means that there is unlikely to be constant health monitoring. The ability to withstand one or more subsystem failures will therefore become a virtue to be pursued during design: we will discuss this at length later in the appropriate section. It may be interesting to see semi-Lagrangian vehicles being employed for special missions (here [7]).

2.2.2. The Dawn of the Gliders: Slocum, Seaglider, and Spray

These main works ([8,9]) present the main features with the pros and cons of the first three vehicles that became technologically established: Slocum, Seaglider, and Spray (see Figure 2). We are faced with a rather classic case in the world of engineering but still surprising: starting from the same requirements, three completely different technological stages were followed, which led to three very different vehicles but with similar general dimensions and performance. The work of Rudnick et al. [10] provides a comparison of both the dimension and performance of the three vehicles, proposing a comparison over a series of missions.

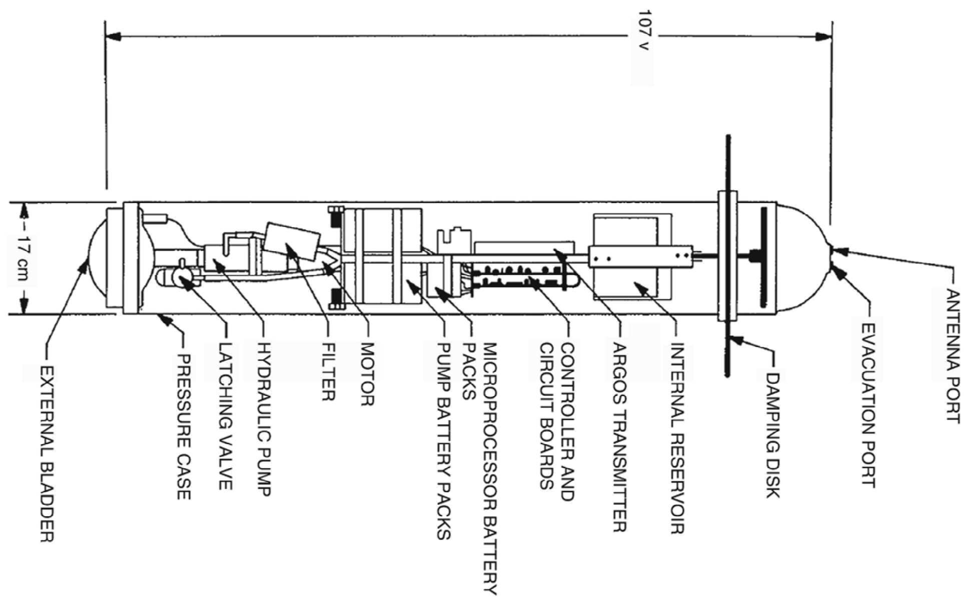


Figure 1. The ALACE Buoy Section.

Figure 2. The three operational gliders (from left to right: Seaglider, Slocum, Spray) (Pierre Testor et al.).

The Teledyne Marine Slocum Glider is a groundbreaking tool for ocean exploration and monitoring; a very accurate description can be found in [11] and an upgrade in [12], together with a general explanation of a new heat engine [13]. The series of missions in which the vehicle can be employed is quite interesting, a mission pipeline [14], mapping icebergs and sea ice [15,16]. The vehicle has become widely used and popular, so much so that there are several studies that determine its simulation [17].

A great description of the AUG spray [18], which explains in detail the general architecture, its development, the communication systems, and justifies the goodness of the fluid dynamic choices with an interesting mathematical introduction to the forces at play and their balance.

A good description of the vehicle can be found here [19], which explains in detail the general architecture, its development, the communication systems, and justifies the goodness of the fluid dynamic choices with an interesting mathematical introduction to the forces at play and their balance. From the hydrodynamic point of view, it is the most interesting and advanced of the three, especially from the hydrodynamic point of view (the full study here [20]): instead of having a uniformly cylindrical body, it has a sinuous "double cone" shape with an elongated front part [21]. Even the maneuvering system based on the rapid movement of a ballast (formed by an auxiliary cluster of batteries) is rather interesting: here too we find a rich mathematical introduction.

2.3. Drone Dynamics

Sub gliders, from a dynamic and kinematic point of view, are a completely new category of vehicles never seen before: we can consider them a cross between a glider and an airship, which, however, operate in a much denser and incompressible fluid. This means that the classical equations of motion of an aircraft are not rigidly applicable and need appropriate adaptations; furthermore, the mathematical model of the airship must also be appropriately adapted since the density gradient is enormously lower.

The general vehicle arrangement can be seen in Figures 3 and 4: obviously not all vehicles are made up of the same parts, or in the positions presented, but it is a sufficient arrangement for a general discussion and to present the type of approach required for the type of study.

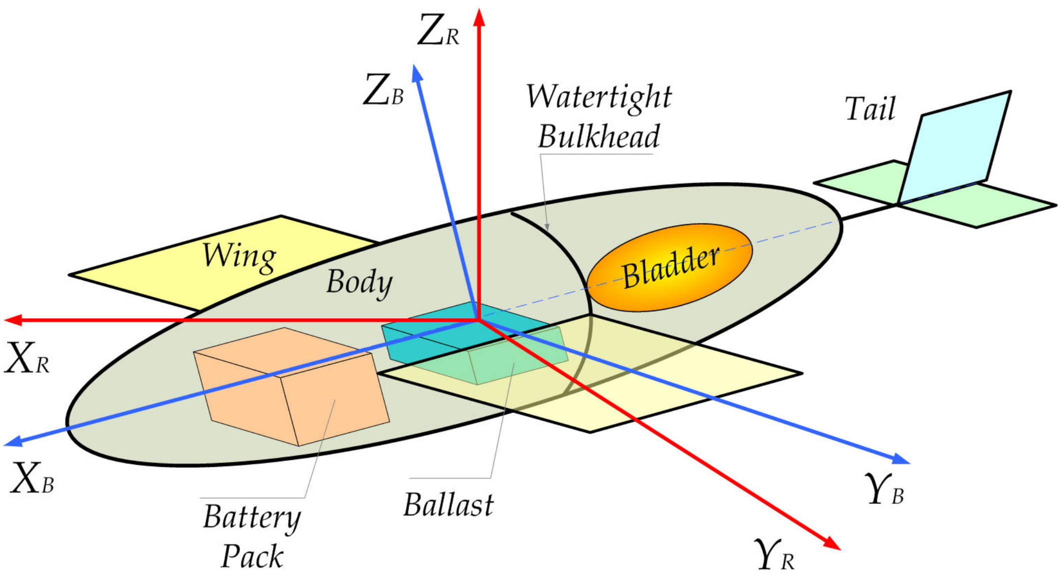


Figure 3. General arrangement of a sub glider.

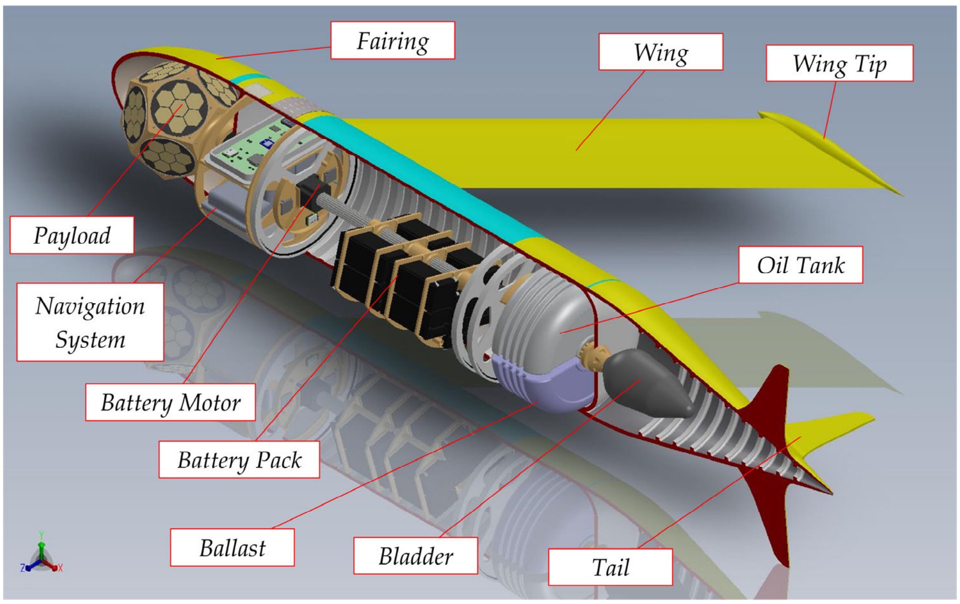


Figure 4. Cutaway of the general arrangement of a sub glider.

The vehicle consists of a body (or fuselage) containing the payload and the various guidance systems (not shown in the drawing), a battery pack, and ballast (fixed or mobile), all contained in the watertight part of the vehicle. The bladder, on the other hand, is in contact with the sea (although contained in a hydrodynamic fairing), as are the wings and tail (in certain architectures this may not be present). The axes integral to the body (X_B, Y_B, and Z_B) and reference (X_R, Y_R, and Z_R) are also represented. A first approach to the organization of the work for the preliminary calculation can be found in the work of Danio et al. [22]: the glider is divided into its main parts, and the analytical process for the dynamic modelling is started.

The complete treatment of modelling can be found in [23] in chapter 3, but a basic but extremely precise treatment of dynamics, which gives an approach to vehicle management and modelling, can be found in the following chapters. The dynamic stability of the vehicle is very important due to the low intrinsic dynamics, with the formula imposing that locally the vehicle must be intrinsically balanced: the application of analysis/simulation (such as CFD and others) can give answers during the design (from [24–27]).

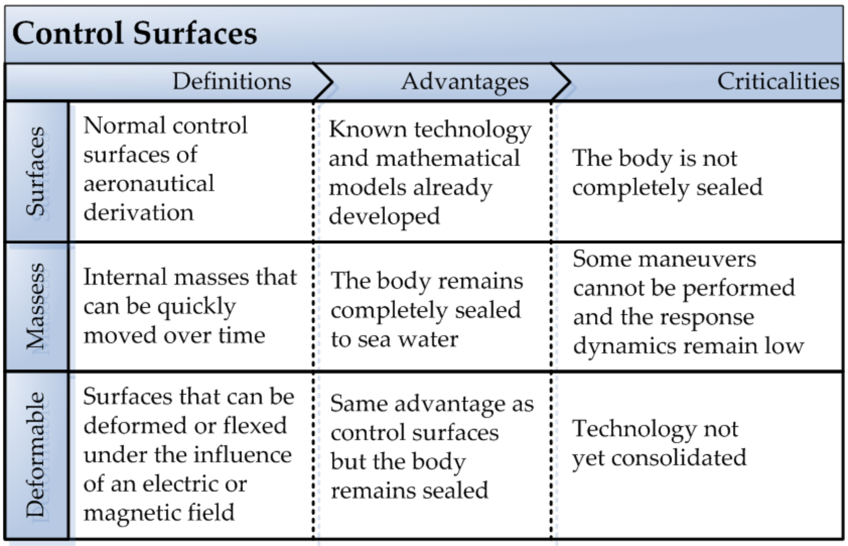
A good simulation of the motion that also takes into account six transients is present in these papers ([28–30]) with a simple simulation: we can establish the exact positioning of the center of gravity and therefore model the inertia ellipsoids.

2.3.1. Depth Control Systems

The depth control system of a sub glider is a key feature that allows it to navigate through the water by controlling its buoyancy and pitch; as said, it uses a combination of buoyancy-driven propulsion and hydrodynamic control to move up and down in the water column and to travel horizontally over long distances. The primary method of depth control in sub gliders is the buoyancy control system, which adjusts the vehicle's density relative to the surrounding water. The variable buoyancy allows the glider to change its buoyancy by taking in or expelling a small amount of water or oil from a bladder or a fixed internal chamber, substantially by changing its volume without significantly altering its mass so the glider can become positively buoyant (float), negatively buoyant (sink), or neutrally buoyant (hover at a constant depth). To achieve this buoyancy change, a device is used to move the fluid into or out of the bladder: when fluid is pumped into the bladder, the glider's density decreases, causing it to rise; when the fluid is expelled, it increases the glider's density, and it sinks. An excellent modelling of the physical problem can be found in the work of Joo, Moon, and Qu, Zhihua [31]; they also provide us with the logic and the mathematical approach. Instead, the variation of buoyancy used as a "dynamic brake" during a descent to depth is well described in the second part of Petritoli et al. [32]. Its use in shallow waters is very interesting: at first glance, it seems that it is a vehicle suitable for operating only in deep waters, but instead, with appropriate measures, it is possible to control it well even in less deep waters ([33,34]).

2.3.2. Direction/Attitude Control Systems

The control methods of an underwater vehicle are crucial for maneuvering and stability: these control functions are similar to those on aircraft but are adapted for operation in a water environment (from [35–41]). There are essentially three ways (see Figure 5) to change the direction and attitude of the vehicle: with classic mobile surfaces (aircraft style), with the rapid movement of one or more internal masses, and with electrically deformable surfaces. This last solution is quite advanced and not yet consolidated in terms of experience but promises interesting developments.



Control Surfaces	Definitions	Advantages	Criticalities
Surfaces	Normal control surfaces of aeronautical derivation	Known technology and mathematical models already developed	The body is not completely sealed
Massess	Internal masses that can be quickly moved over time	The body remains completely sealed to sea water	Some maneuvers cannot be performed and the response dynamics remain low
Deformable	Surfaces that can be deformed or flexed under the influence of an electric or magnetic field	Same advantage as control surfaces but the body remains sealed	Technology not yet consolidated

Figure 5. Control methods/surfaces of an underwater vehicle.

A very interesting control system is found in [42–44]: instead of moving the tailplanes, here the wing pitch is changed independently. In the paper, we find a complete model, and the solution has very notable strong points, such as, for example, a very high dynamic. On the other hand, it imposes a considerable weight price in case of scale-up; furthermore, the solution is applicable to gliders with a classic architecture: a "flying wing" system would find a series of difficulties in arrangement.

Deformable materials, as mentioned before, are the latest frontier of practical applications on an underwater drone: they give the great advantage of operating as an actuator but without the need for a mechanical connection between the resistant hull and the surface immersed in the water flow. The memory material has a "before" and an "after" or assumes two reasonably stable mechanical configurations before and after its actuation, which can occur by thermal, electrical, or magnetic means. Discarding for obvious reasons the thermal stress in our case, we will examine the behavior and the type of materials that are influenced by the other two parameters (from [45–49]). There are also some interesting applications of pitch control via fuzzy logic: the Takagi Sugeno method allows the faster resolution of differential equations [50].

2.3.3. Blended Wing Architecture

A blended-wing architecture offers several advantages over other types of designs that come from the hydrodynamic properties of the wings and their contribution to stability, efficiency, and overall performance (see Figure 6). The streamlined shape of fixed wings, especially with optimized aerofoil designs, reduces drag, enabling faster speeds and more efficient flight compared with other configurations. The design of blended wings provides excellent control and stability during flight; this makes the vehicle more stable and easier to handle, especially in challenging environmental conditions. The preliminary work by W. Zihao et al. [51] is interesting, as it clears the field from the first problems of general architecture, while a more accurate analysis can be found here [52], where a mathematical–computational approach to the vehicle and its stability is proposed.

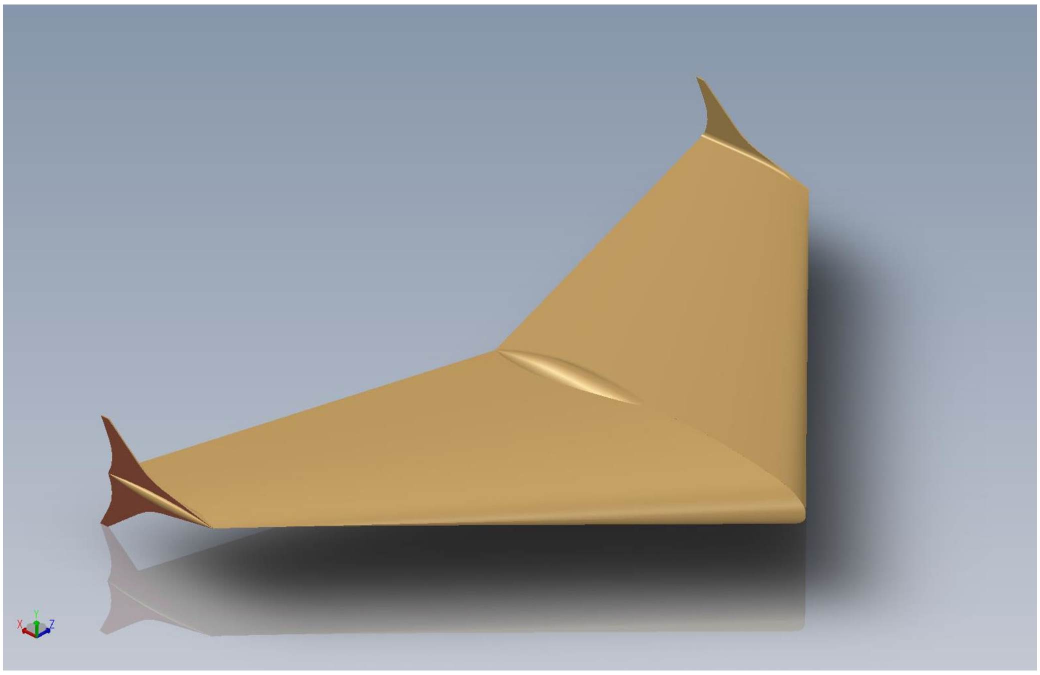


Figure 6. A blended wing configuration in a CAD rendering (Manta Project).

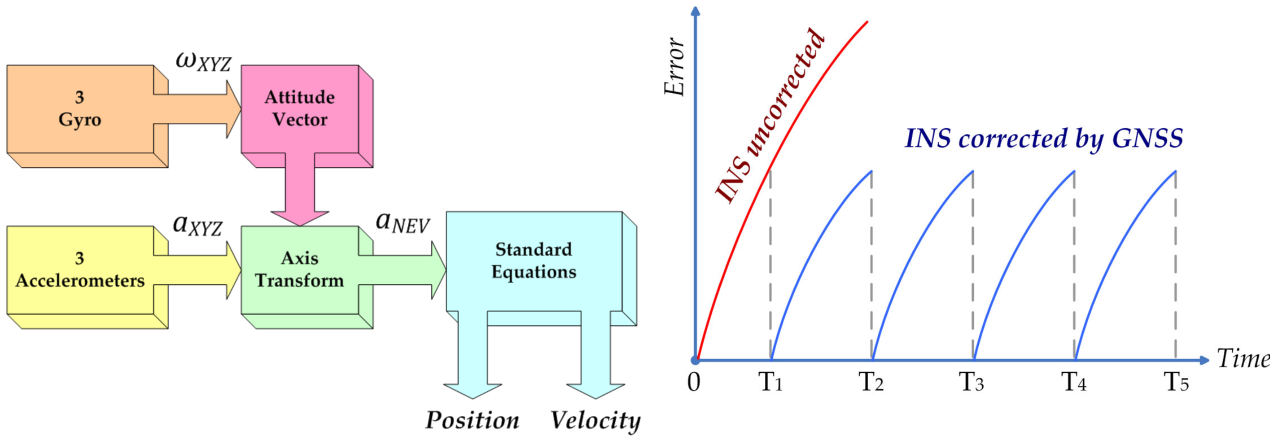
In Q. Huang et al. [53], the behavior of the aerofoil is explored, while in Sun et al. [54], the fusion between the "body" and the wing itself is optimized: the problem of the hydrodynamic design of this type of vehicle is precisely that of making the best use of the formula by fluidly merging all the components.

2.4. Positioning and Navigation

Navigation (connected to attitude) and precise positioning are very strong and heartfelt topics for underwater gliders: to have an overall view of the state of navigation systems, it is useful to start from the survey by G. Fan et al. [55], which provides us with a useful overview, especially because it highlights the critical points and strengths of the various systems.

At the beginning of the development of this type of vehicle, the system of submarine boats was borrowed, i.e., once on the surface, the position was determined with a simple GNSS-type satellite receiver that provided an error on the position less than the size of the "average glider" and therefore more than acceptable to us: once left alone in the dive, the signal immediately faded, and we made use only of the inertial reference (INS platform—see Figure 7a) [56–58]. Since, by definition, the full-immersion phases of missions are always very long, we cannot ignore the increase in error as time goes by in inertial systems and cyclic errors that have a long period and thus are comparable with the aforementioned immersion time and cannot be ignored in the discussion, found in the following Table 1 (for a detailed and comprehensive discussion of progressive error in inertial systems from [59–61]).

Since the sum of these errors increases over time, it is necessary that, at the first emergence, the vehicle makes a fix with the satellite system (see Figure 7b) and reduces the error almost to zero. The IND and GNSS systems compensate each other since the satellite does not allow a continuity of navigation if the vehicle is stationary ("GDOP jump" problem, see [62–65]).



(**a**) (**b**)

Figure 7. (**a**) Block diagram of a strapdown INS reference system, (**b**) Error drift over time of an uncorrected and a GNSS-corrected INS system.

Table 1. Main errors of the INS systems.

Name	Description	Value
Time drift	Because of the double integration present in the loop, the natural instrumentation error is amplified over time (refer to Figure 7a)	$\propto t$
Schuler's oscillation	Periodic error $T \approx 84.4$ min	$\omega_s = \sqrt{\frac{g}{R_0}}$
Foucault's oscillation	Periodic error $T = \frac{2\pi}{\Omega sinL} \approx 30\ h$	$\omega_f = \Omega sinL$
24 h Oscillation	Periodic error $T = 24\ h$	$\omega_e = 15^\circ/h$

The fusion of data from the two systems is necessary because the position provided by the INS compensates for the intrinsic precision instability of the satellite system (see [66,67]).

The authors clarify that the previous discussion does not have the aim of designing a navigation system, as it is far from the purpose of this work, but to explain why it is necessary to merge the position data coming from two such different systems; furthermore, from a commercial point of view, there are already "turnkey" systems ready to be integrated into more complex systems.

Subsequent technological development has allowed the integration of many more sensors into the drone's navigation system, which can contribute to maintaining high navigation precision. The work of Alamleh et al. [68] is very interesting from this point of view as it provides a nice overview of other navigation aids. It all revolves around the interaction between the basic information derived from the INS, the GPS (received on the surface or via a string buoy), and the image of the environment generally obtained via optical or acoustic spectrum and compared with the internal image preloaded in the navigation system. Optical systems are very precise but do not allow an extended range like the less precise but higher-capacity acoustic systems.

The threat brought by the complex marine environment to the navigation safety of sub-vehicles, a navigation safety situation evaluation method based on D numbers theory is presented in [69] after considering the plane ocean current impact.

Disturbance by rapidly varying flows and currents induces a serious error in the inertial system: here is a series of solutions to the problem, also by SW (from [70–74]).

As for swarm cooperative interactions, we have dedicated a specific section to them.

2.4.1. Acoustic Navigation

In this section, we will place all the works that require or interact with the seabed map. This, as previously said, can be obtained acoustically: the information thus obtained can be compared with the preloaded models or constitute an intrinsic anti-collision system with the seabed. In all cases, the precise and punctual mapping of a seabed segment remains developed and recorded. To properly approach the problem of this type of navigation, it is necessary to examine the survey by G. Fan et al. [75], which leads us to a first outline of the main systems, methodologies, and possible problems.

It is necessary to mention the works of Nygren et al. (from [76–79]), who explore the topic both from the point of view of data acquisition and their correlation. In the last one in particular [80], an interesting temporal correlation through Kalman filters is proposed. Interesting research is the orientation through acoustic radio beacons for a sub glider: these allow (thanks to Kalman filters) the underwater spatial localization of the vehicle [81]. Matching the terrain, when preloaded, is not easy; here a simplification algorithm for the model is proposed to optimize the recognition capability by means of a multibeam sonar [82]. A good navigation method based on Bayesian estimation helps both the recognition of the seabed and the reduction in false echoes [83]: the Bayesian estimation updates the probability of a hypothesis as more evidence or data becomes available; it differs from classical (frequentist) statistics by treating unknown parameters as random variables and using probability distributions to represent uncertainty. Another method, always of the Bayesian type, is based on the fusion of data coming from the inertial IMU with those coming from different acoustic sources (beacons) (from [84–87]). Also in these works ([88,89]), an interesting fusion between the rather inconstant data coming from the sonar with those of the inertial system, which provides information on the continuity of the movement, is proposed.

2.4.2. Visual Navigation

When the visibility of the water allows it, it is always better to rely on a visual type of navigation, that is, in the visible band and, where it allows it, in the multispectral; this allows you to have a clear view of the area in which you are working: one of the classic applications is ocean pipelines and oil extraction platforms. The use of multiple stereoscopic cameras with appropriate algorithms can be found in the works of Eustice et al. [90] and Salvi et al. [91]. It is possible to use the vision of the seabed in a totally passive way; that is, recognition is not necessary, but the optical triangulation between different points of interest can provide us with speed and trim data that, if integrated, allow us to reconstruct the trajectory travelled ([92–94]). The fusion between the various sensors can also be achieved between the data coming from the inertial systems and the optical image of the seabed, appropriately mediated by a series of Kalman filters [95]. Although it was not developed for SGs only, we have here a series of works (from [96–98]) based on a monocular optical guidance system, which therefore does not require stereoscopic vision.

2.5. Communications

The surface communication systems of the drones are the same as those of normal ships, i.e., the GNSS system for positioning and the normal constellations in low orbit for communications (Inmarsat, Iridium, etc. [99]), and, to be found at short range, simple beacons in UHF/VHF. Classic HF communications are avoided (until not so long ago, very normal on ocean-going ships) because they present two difficulties: the excessive length of the antennas that far exceeds the size of the drone, and their positioning very close to the liquid surface does not improve the quality of transmission. Furthermore, the related electronics are very heavy in relation to the vehicle and energy-hungry; therefore, they are incompatible with these architectures [100]. The presence of multiple drones and different vehicles in the same stretch of sea brings new challenges from the communication point of view, which leads to optimizing frequencies and signal types [101].

Although still under strong development, we would like to point out this interesting survey on underwater optical communications [102].

2.6. Payloads

The drone is undoubtedly its own payload; that is, its mission is essential to the vehicle, so it is necessary to maximize the overall efficiency to be able to complete its purpose. Obviously, the payloads are almost infinite, from the search for the seabed to the analysis of the plankton; in this section we will propose the most interesting and rich in development points.

One of the first and most natural applications is the drone as a vector for transporting the sonar [103] to the bottom, without paying the price of having to cross a large thickness of water: since the sonar transducer cable cannot be too long, its use in medium–high depths is ideal.

Acoustic tomography arrays are specialized systems used to map the physical properties of water, such as temperature, salinity, and current velocity, by analyzing the travel times of sound waves. This method relies on the principle that the speed of sound in water varies with these properties, allowing researchers to create detailed profiles of ocean conditions (from [104–107]). These systems are a powerful tool for a vector such as a sub glider, providing valuable data on the physical properties of seawater over large areas, and the ability to register onboard real-time information makes them essential for studying ocean dynamics, climate change, and the health of marine ecosystems [108].

An interesting application of the "Spray" drone is to investigate the California Current System (CCS) (from [109–113]), the behavior of its effluents, the effects of El Niño, and the various temperature gradients.

In the works of J. C. Gradone et al. [114] and from [115–117], an interesting application is proposed, namely an acoustic Doppler system to profile the various marine currents.

2.7. Swarm

The definition of *swarm* refers to a group of drones that operate collaboratively and autonomously to achieve a common objective. These swarms can consist of a few drones or hundreds, depending on the mission requirements, and often employ algorithms inspired by natural systems like insect swarms; they have numerous applications in fields such as rescue operations, disaster response, exploration, and environmental research. One of the greatest strengths is the tolerance for failure: if one or more drones fail or are incapacitated, the swarm can continue functioning, as the remaining drones can adapt and redistribute tasks, ensuring mission continuity. Furthermore, the decentralized nature of the system ensures that no single point of failure exists, making the system more robust against mechanical failures or environmental attacks.

Swarms can make collective decisions based on shared data and sensor inputs, allowing them to respond dynamically to changing environments or mission objectives. Hence the concept of "intelligence balance": the more the links between the various vehicles are "loose" and less deterministic, the greater the decision-making autonomy of the individual drone must be (stochastic approach), and vice versa: the more deterministic the approach to swarm management, the less stochastic the management of the individual drone is.

One of the most interesting challenges for the drone swarm is to "fly" in close formation and maintain it for the entire journey: one of the proposed solutions ([118,119]) is an algorithm in which a "squadron leader" who relies on an inertial system INS: all the rest of the formation processes the relative distance (vector) with respect to him.

An interesting method of swarm orientation is the acoustic one (from [120–123]): either ambient noises or appropriate impulses generated by the various members of the swarm can be used.

The use of a cluster of independent and centrally piloted drones allows for detailed data collection of the underwater environment [124]: this solution is much cheaper than a series of fixed measuring stations and allows for greater flexibility. The best method to explore a sea area is to make vehicles reasonably autonomous [125]: firstly, formation control strategies useful for sampling small spatial scale processes are designed; secondly, mobile sensor networks are used to provide synoptic coverage to investigate larger scales (up to 100 km). For seabed mapping, an algorithm that optimizes the swarm effort and time is needed [126].

2.8. Drones Reliability

The reliability of this type of AUV is an extremely critical parameter: long missions in hostile environments mean that the drone is left alone and unassisted, so that any serious failure leads to at least the cancellation of the mission if not the loss of the vehicle itself. The question often asked of "reliability engineers" is: "what is it that makes a system reliable and how do you know how reliable it is?" The answer is often quite complex: not just one aspect of the development process makes a product reliable, but a broad combination of elements such as good product design, the approach methodology adopted, good development and process control, and consistent quality in production.

So far, the reliability of an element has been discussed without concern for its complexity.

We now look at the relationships that link the reliability of a complex system (see Figure 8) to that of its individual components. In mathematical terms, the relationship is expressed as

$$R_{sys} = f[R_1(t),\ R_2(t),\ R_3(t),\ R_4(t),\ R_5(t), \ldots R_N(t),] \quad (1)$$

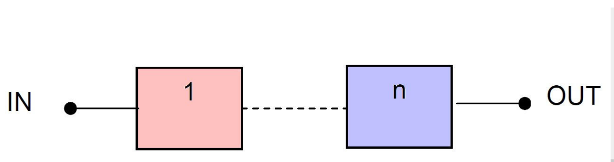


Figure 8. Block diagram of a reliability system.

Posing λ_i as the reliability of the single part of the system composed of N units, the reliability over time is given by

$$R_{sys} = \prod_{i=1}^{N} R_i = \prod_{i=1}^{N} e^{-\int_0^t \lambda_i(t)dt} = e^{-\sum_{i=1}^{N}\int_0^t \lambda_i(t)dt} = e^{-\int_0^t \sum_{i=1}^{N} \lambda_i(t)dt} = e^{-\int_0^t \lambda_{sys}(t)dt} \quad (2)$$

A first approach to system reliability for a drone can be found in Leccese et al. [127]: although there is no specific literature dedicated to sub gliders, the approach to examining the reliability of a generic drone is perfectly applicable to our sub gliders. In Ciani et al. [128], we find a different approach: once a specific architecture is selected (after a trade-off phase), the reliability assessment becomes a key issue to optimize the design and to evaluate the intrinsic reliability at the design stage of the vehicle. Lately, given the strong interconnection between the various units present in the vehicle, it could be interesting to address its reliability by considering it as a complex system: in the face of a greater complication from the conceptual point of view, we arrive at a better determination of its reliability and its maintainability (refer to [129,130]).

Markov analysis is a powerful tool for studying stochastic processes, especially in scenarios where system states evolve over time with well-defined probabilities. In our case, it helps us to manage a whole series of subsystems or to observe the effect of the loss of one or more functionalities (compound failure). In Figure 9, there is an example of a compound failure Markovian tree of a simple schematic system of a drone: the various logic gates are the synthesis of how two or more failures lead to the loss of a complete system or to some of its important functionalities (events 01 to 14 are for explanatory purposes only).

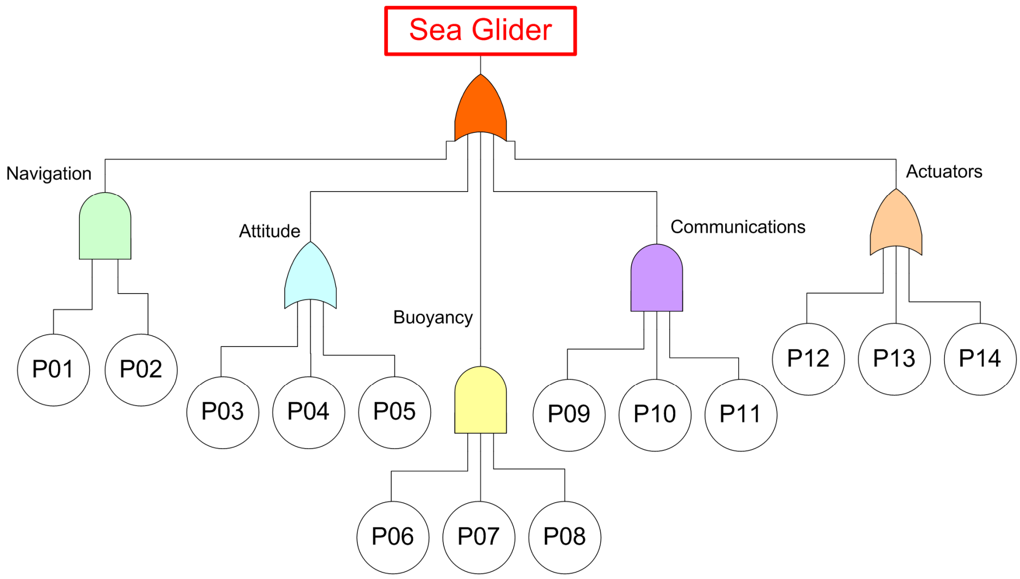


Figure 9. A simple Markov analysis of drone subsystems (events 01 to 14 are for explanatory purposes only).

3. Current Challenges and Future Research Directions

It is extremely difficult to predict the future of underwater gliders because they have the "curse" of being old-but-young since their general architecture dates back more than a quarter of a century ago, but they are at the center of a technological race to see who can use the latest technology or employ them in the newest or most useful way. Of course, having a relatively inexpensive vehicle capable of navigating for weeks is a temptation for many researchers who will use it with ever-changing payloads, condemning it to eternal development and updating as is already happening with the airplane. Since the authors do not (yet) possess the ability to predict the future, the interest is focused on the technological problems illustrated in the initial chapters.

3.1. One Step Beyond

To take an engineering approach to the development of new vehicles that can meet old and new requirements, i.e., to know 'the shape of things to come', it is necessary to examine the work of Jenkins et al. [131]. Starting from the performance, strengths, and weaknesses of the three classic AUGs (Slocum, Seaglider, and Spray), and imagining old and new tasks, they project new developments into new application scenarios. In addition to the undoubtedly interesting results, it is necessary to examine the methodologies: in 244 pages, they provide numerical indices and objective data for comparing the various vehicles. It is also interesting to note that this approach is interdisciplinary because it ranges from hydrodynamics to mechanics, from navigation to communication systems.

3.2. Current Challenges

The current challenges are precisely overcoming the most critical points related to the general architecture of the aircraft and overcoming technological limits: while the latter, with the help of time, are slowly eroded by the advancement of research, the critical points can only be circumvented. The topics that still require a large margin of improvement are as follows:

- Improving the dynamics and general maneuverability of the AUG: more refined research of the hydrodynamics of the system can certainly lead to significant improvements, especially from the point of view of autonomy. Parallel research on the maneuvering surfaces, on their effectiveness and positioning, will certainly improve the response to the commands.
- Provide a system to vary the attitude at zero or low speeds: this is currently only possible by using small vectorizable electric motors that drain a lot of power reserve (autonomy).
- Develop new internal architectures to reach ever greater depths in order not to sacrifice too much of the volume dedicated to the payload.
- New communication systems and new employment philosophies to optimize the performance of the drone swarm.
- New visual systems for the recognition not only of the seabed (for navigation purposes) but also of the smallest objects present in the environment to obtain a vehicle capable of operating more effectively in research.

3.3. Future Research Directions

Having carefully evaluated many lines of research, the natural development is to shift the focus of research precisely on the weak points that are inherent to the vehicle, trying to improve its performance not only through simple optimization but also by entering completely new fields of research and exploring the possible possibilities of its use.

3.3.1. Autonomy and Range

The first point of development is that of autonomy, that is, making the vehicle less and less dependent on batteries and trying to exploit the thermal jump due to the change in depth associated with a change in temperature of the salt layers. Practically in the sawtooth movement, we go from rather high surface temperatures to increasingly lower temperatures towards the bottom: although it is not a very recent idea, we try to exploit the thermal jump by making liquid (usually oil) evolve in a secondary circuit with the aim of pressurizing a gas accumulator and then using it in different ways. All this in order to conserve the batteries as much as possible: we can find interesting research ideas here [132,133], although it is not very recent work.

3.3.2. Solar Cells

The fusion between solar cells and AUG has soon become a reality [134,135]: now the "reverse U-boat system" is being used, that is, while the old submarines travelled on the surface at night with diesel propulsion to recharge their batteries, today the drones stop on the surface during the day for the same purpose. The main problems of this power supply system are not negligible, although surmountable; the main one is the increase in weight: the vehicle suffers from the non-negligible weight of the solar cells, the harness, and the power management electronics. Furthermore, the panels cannot be in direct contact with seawater, so they require transparent shielding (which decreases their efficiency) and water sealing. From an operational point of view, it is obviously affected by the weather conditions of the surface, and, if they are optimal, it must lie on the surface until the batteries have reached the desired charge. Finally, the solar panels require a very considerable external surface of the vehicle, which is, by its nature, the minimum possible, so their extension will be equally sacrificed.

3.3.3. The AI in Underwater Gliders

The integration of Artificial Intelligence (AI) into underwater drones is poised to revolutionize marine exploration, monitoring, and operations: it enables these drones to operate autonomously, adapt to changing underwater environments, and perform complex tasks with minimal human intervention.

AI algorithms allow drones to navigate complex underwater terrains without GPS, relying on techniques such as SLAM (Simultaneous Localization and Mapping) and allowing dynamic path adjustment: a real-time course correction based on environmental changes, avoiding obstacles like rocks, debris, or marine life. AI-powered swarms can coordinate tasks like large-scale mapping or searching, increasing efficiency and ensuring continued operation even if one drone fails. The machine learning models use vast datasets to train drones for recognizing underwater objects, identifying shipwrecks, or mapping the ocean floor and enhance predictive capabilities for identifying underwater hazards or resource-rich areas.

The major problems that are therefore an inherent challenge are as follows:

- Training AI models requires extensive, high-quality underwater datasets, which are often scarce.
- AI systems demand significant computational power, potentially straining battery resources in prolonged missions.
- Underwater environments are unpredictable, with challenges like murky water, high pressure, and unpredictable currents.

The future of AI holds immense potential, enabling smarter, more efficient, and safer underwater operations: as advancements continue to integrate with cutting-edge hardware, sub drones will play a pivotal role in marine science, industry, and security, unlocking the mysteries of the deep ocean like never before.

3.3.4. Adaptive and Smart Materials

Adaptive and smart materials are innovative substances capable of responding dynamically to environmental changes, external stimuli, or operational demands. These materials play a vital role in advanced engineering applications, including robotics, aerospace, biomedical devices, and underwater technologies. They have important characteristics to react to stimuli such as temperature, pressure, light, pH, or electromagnetic fields; to return to their original state once the stimulus is removed; and are adaptable to various applications by altering properties or configurations.

The main categories are as follows:

- Shape Memory Materials (SMMs) that recover a predefined shape when subjected to specific conditions. Nickel-titanium (Nitinol) alloys used in stents and actuators; Shape Memory Polymers (SMPs) Thermoplastic polymers for self-deploying structures or used for morphing fins.
- Piezoelectric Materials that generate electrical charge in response to mechanical stress or vice versa are used for sonar transducers in underwater vehicles.
- Magnetostrictive Materials that change shape or dimensions under magnetic fields.

- Electroactive Polymers (EAPs) that deform when exposed to an electric field used for the flexible actuators for UV.
- Self-Healing Materials that automatically repair damage, extending the material's lifespan based on polymers embedded with microcapsules of healing agents employed in bio-inspired materials that mimic natural healing processes.
- Phase-Change Materials (PCMs) that store and release energy during phase transitions (solid to liquid or vice versa), such as paraffin wax or salt hydrates. Used in internal thermal management systems (thermal pumps).
- Responsive Hydrogels that expand or contract based on environmental changes such as pH, temperature, or moisture.

Adaptive and smart materials are transformative, offering dynamic solutions to complex challenges. By leveraging their unique properties, they enable innovation across various fields, shaping a smarter and more responsive technological future.

These materials are bringing about a radical change to the design and performance of submarine drones, enabling them to operate more efficiently in dynamic and challenging underwater environments.

3.3.5. Future of Swarms: The SaaS

The Swarm as a Service (SaaS) is an emerging concept where drone swarms are offered as a scalable, on-demand solution for a variety of applications; it is very similar to cloud computing services: SaaS aims to provide access to advanced drone capabilities without requiring organizations to invest heavily in the infrastructure, hardware, or expertise needed to deploy and manage swarms.

Clients can request drone swarms of varying sizes based on the scope and complexity of their missions; dynamic adjustments are allowed for adding or reducing swarm members in real time and can be customized for specific tasks such as surveying, inspection, or deep-sea exploration. The swarms provide live data feeds, enabling immediate analysis and decision-making thanks to integrated cloud solutions that allow us to access processed data remotely. Environmental monitoring is an important task for the vehicles, such as mapping ecosystems and seabeds, monitoring wildlife, and detecting environmental changes. When necessary, it is possible to do on-demand monitoring of pollutants or hazardous substances.

This kind of architecture eliminates the need for upfront investments in drone hardware and software: the services are paid for by the client only when needed, making it budget-friendly. Swarm as a Service has the potential to revolutionize industries by making drone swarm technology accessible, efficient, and scalable. As technology advances, SaaS will likely become a cornerstone of smart automation and autonomous operations in diverse fields.

4. Conclusions

Our work was born after several years of study and application in the field of underwater gliders: we are far from claiming to cover all the knowledge on the subject; our aim was to provide a sort of roadmap that is useful both for those who approach the subject for the first time and for those who have been dealing with it for many years and are looking for ideas or particular topics.

The work was born from the need of our work group to give a simple guide to the enormous number of excellent papers on the subject; we therefore take this opportunity to point out that among all of them we had to make a selection for the sake of brevity, for which we are already thinking about developing a further systematic–methodical integration to this work, which, by its nature, has been restrictive.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
ALACE	Autonomous Lagrangian Circulation Explorer
AoA	Angle of Attack
AUG	Autonomous Underwater Glider
AUV	Autonomous Underwater Vehicle
CFD	Computational Fluid Dynamic
CG	Centre of Gravity
COTS	Commercial Off the Shelf
DPA	Dynamic Path Adjustment
EAP	Electroactive Polymers
FTA	Fault Tree Analysis
GDOP	General Dilution of Precision
GLONASS	Global Navigation Satellite System (Russian Navigation System)
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System (Navstar GPS)
IMU	Inertial Measurement Unit
MTBF	Mean Time Between Failures (=MTTF+MDT)
PCM	Phase-Change Materials
RAMS	Reliability, Availability, Maintainability and Safety
SG	Sub Glider
SLAM	Simultaneous Localization and Mapping
SMM	Shape Memory Materials
SMP	Shape Memory Polymers
S/S	Subsystem
UAV	Unmanned Aerial Vehicle
UG	Underwater Glider

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