



Autonomous Marine Systems: Evolution, Engineering Architecture, and Operational Benefits — A Review

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Abstract

Autonomous Marine Systems (AMS) are evolving from specialized research platforms into practical engineering assets for ocean observation, hydrographic survey, subsea inspection, environmental monitoring, and maritime operations. This review examines the evolution and classification of autonomous underwater vehicles (AUVs), underwater gliders, unmanned surface vehicles (USVs), hybrid systems, and cooperative architectures from an engineering perspective. Particular attention is given to the coupled design of hull geometry, hydrodynamics, structural materials, propulsion, energy storage and harvesting, guidance-navigation-control, sensor and payload integration, and marine communication. The review evaluates how these engineering choices influence speed, endurance, depth capability, maneuverability, payload capacity, navigation accuracy, data quality, reliability, and operational cost. Representative platform classes including REMUS, HUGIN, Slocum, Seaglider, Spray, Saildrone, and Wave Glider are used to illustrate alternative design philosophies and mission trade-offs. The principal operational benefits of AMS include reduced personnel exposure, improved access to hazardous and remote environments, repeatable data collection, reduced dependence on support vessels, and increased spatial and temporal coverage. The paper argues that successful AMS development requires multidisciplinary systems engineering in which vehicle architecture, propulsion, energy, sensing, navigation, communication, and mission requirements are considered as a coupled design problem. This engineering perspective provides a foundation for understanding the persistent challenges and future technologies addressed in a companion review focused on resilience, autonomy, and lifecycle engineering.

Keywords

Autonomous Marine Systems (AMS); Autonomous Underwater Vehicles (AUVs); Unmanned Surface Vehicles (USVs); Marine Engineering; Hull Design; Propulsion; Energy Systems; GNC; Sensor Integration; Subsea Communication.

1. Introduction

The ocean is an unusually demanding operating environment for engineered autonomous systems. A vehicle must function in a fluid that is continuously moving, corrosive, difficult to sense through, and often inaccessible to direct human intervention. Pressure increases rapidly with depth, sea state can change mission conditions within hours, and underwater radio-frequency propagation

is severely restricted. These characteristics mean that autonomy at sea is not simply a software problem. It is a whole-system engineering problem in which mechanical design, propulsion, energy, sensing, navigation, communications, control, software, and operational logistics must remain functional together.

The development of autonomous underwater vehicles began in earnest in the 1970s and

accelerated as compact computing, inertial sensors, acoustic navigation, batteries, and embedded control became available. The resulting platforms have moved from experimental research machines to operational systems used for mapping, oceanographic sampling, mine countermeasures, infrastructure inspection, environmental monitoring, and search operations [1]. Navigation has remained a central constraint because GPS and ordinary radio links cannot be used continuously while an AUV is submerged. As a result, modern AUVs combine inertial navigation with velocity, depth, acoustic, terrain, or visual references [2].

The field is now broad enough that the term Autonomous Marine Systems should be understood as an umbrella for multiple vehicle classes and their supporting infrastructure. AUVs operate beneath the surface; USVs operate on the surface; gliders exploit buoyancy and hydrodynamic lift for very low-power movement; hybrid systems can move between surface and subsea domains; and cooperative fleets distribute sensing, computation, and communication across several vehicles. A recent review of AUV technologies emphasizes the convergence of vehicle design, power, planning and control, perception, navigation, communications, and artificial intelligence, confirming that progress is increasingly driven by integration rather than isolated subsystem improvements [3].

For engineers, the important question is not whether a vehicle is autonomous in an abstract sense. The important question is whether the selected autonomy architecture can complete the mission with acceptable risk, endurance, data quality, maintainability, and cost. A survey vehicle that can navigate accurately for twelve hours may be more valuable than a nominally more autonomous vehicle that can remain at sea for only two hours. Similarly, a high-bandwidth communication system is not automatically better if it consumes excessive power or works only over a short optical line of sight. The correct design is therefore mission-dependent.

This review adopts that practical engineering viewpoint. It focuses on the equipment, interfaces, design trade-offs, operational benefits, persistent limitations, and emerging technologies that will

determine whether autonomous marine systems can move from successful demonstrations to dependable industrial assets. The review is intentionally interdisciplinary but avoids treating artificial intelligence or autonomy algorithms as independent objectives. Instead, they are evaluated according to how they improve the performance and reliability of the complete marine system.

The review first examines the evolution and classification of autonomous marine platforms, then addresses the engineering subsystems that determine vehicle performance, and finally evaluates the practical benefits of deploying autonomous systems in marine operations.

Table 1 places the present AMS landscape in historical context. The progression is not a simple replacement of older technologies. Instead, new capabilities have been layered onto mature deterministic control, navigation, and mission-planning architectures. This explains why practical systems often combine conventional engineering with selective AI functions rather than relying on end-to-end machine learning.

2. Evolution and Classification of Autonomous Marine Systems

As illustrated in **Figure 1**, the evolution of autonomous marine systems has produced a diverse range of vehicle architectures, with differences in size, hull configuration, propulsion, energy capacity, payload integration, and operational depth reflecting the specific engineering requirements of different marine missions.

2.1. Autonomous Underwater Vehicles

AUVs are the most direct expression of autonomous subsea engineering. Their defining characteristic is freedom from a physical tether to a support vessel. This allows them to survey large areas, operate near the seabed, and collect measurements without the drag and handling limitations associated with a cable. The trade-off is that the vehicle must carry its own energy, navigation capability, mission computer, safety logic, and recovery strategy. These requirements make AUV architecture fundamentally different from that of an ROV.

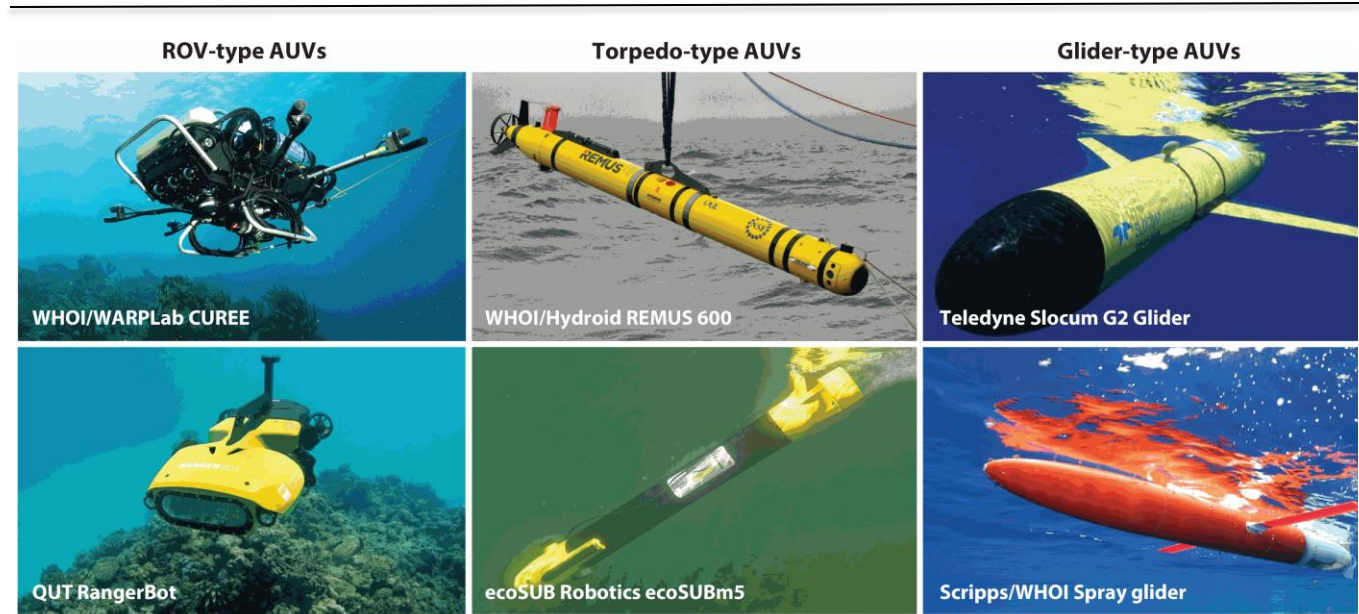


Figure 1. Evolution and classification of Autonomous Marine Systems [3].

Table 1. Key technological milestones in AMS development

Period	Representative development	Engineering significance
1970s–1980s	Early experimental AUVs and autonomous navigation	Established unmanned subsea mission concepts
1990s	Compact AUVs and operational gliders	Reduced deployment burden and improved endurance
2000s	REMUS, HUGIN, Slocum, Seaglider, Spray	Transition toward repeatable field operations
2010s	Long-endurance USVs and networked AUVs	Persistent observation and multi-platform missions
2020s	AI-enabled perception, docking, hybrid communication	Greater adaptation and reduced operator workload
Emerging	Energy-aware fleets and deep-sea autonomy	System-of-systems and persistent autonomy

AUV configurations range from small portable vehicles to large deep-water systems. Compact torpedo-shaped vehicles are often selected for hydrographic survey and environmental monitoring because they can be launched from relatively small vessels. Larger vehicles provide greater energy and payload capacity and can support sophisticated sonar, optical, and environmental packages. The distinction between vehicle size and mission capability is important: a small vehicle with a well-selected payload can outperform a large vehicle when deployment logistics dominate project cost.

Navigation is a defining subsystem in AUV operations. A review of AUV navigation and localization identifies dead reckoning, acoustic

positioning, map matching, integrated navigation, and SLAM as major approaches [2]. Cooperative navigation adds another layer by allowing several vehicles to share measurements, but it also makes the communication and synchronization problems more difficult. A practical system therefore uses a hierarchy: inertial sensors provide high-rate short-term motion, DVL provides bottom-relative or water-relative velocity when conditions permit, depth sensors constrain the vertical state, and acoustic or terrain references reduce long-term drift.

Figure 2 compares a representative torpedo-type AUV with three established buoyancy-driven underwater glider families—Seaglider, Slocum,

and Spray—using propulsion principle, endurance, speed, payload capacity, and operating depth as key engineering performance parameters. The comparison demonstrates a fundamental trade-off between propulsive capability and endurance in autonomous underwater vehicle design. The torpedo-type AUV employs an electrically driven propeller and continuous active propulsion, providing substantially higher speed, maneuverability, and payload capacity than the glider platforms. These characteristics make actively propelled AUVs particularly suitable for missions requiring rapid transit, precise trajectory following, inspection, intervention, complex seabed surveys, and the operation of relatively power-intensive payloads. Their principal limitation is the comparatively high energy demand associated with continuous propulsion, which constrains mission endurance according to available battery capacity and vehicle power consumption. In contrast, Seaglider, Slocum, and Spray use buoyancy-driven propulsion, in which changes in vehicle buoyancy and internal mass distribution generate vertical motion that is converted into forward gliding motion. This operating principle substantially reduces propulsion energy consumption and enables missions extending over several months, although at considerably lower speeds and generally with more limited payload capacity. The differences among the glider configurations further illustrate how propulsion and vehicle architecture can be tailored to specific mission requirements; for example, the Spray configuration provides greater operating-depth capability, whereas Seaglider and Slocum emphasize long-duration, energy-efficient ocean observation. These characteristics demonstrate that there is no universally optimal autonomous marine platform; instead, vehicle architecture must be selected according to the required combination of speed, endurance, payload, operating depth, maneuverability, and environmental conditions

2.2. Underwater Gliders

Underwater gliders represent a different engineering philosophy. Instead of generating

continuous thrust, they change buoyancy and use wings to convert vertical movement into horizontal travel. The resulting speed is modest, but the power requirement can be dramatically lower than that of a propeller-driven AUV. This trade-off has enabled missions lasting weeks or months and has made gliders particularly valuable for persistent ocean observation [4].

Slocum, Seaglider, and Spray are foundational examples. The original Slocum concept demonstrated environmental-energy propulsion through a thermal engine [5]. Seaglider demonstrated long-range autonomous profiling with very low hydrodynamic drag and satellite-based surface communication [6]. Spray demonstrated a compact buoyancy-driven platform capable of long-range profiling using wings and a buoyancy engine [7]. Later operational experience with Slocum showed that fleets of relatively inexpensive vehicles could provide long-duration spatial and temporal observations [8].

The glider architecture illustrates a general engineering principle: endurance can be increased not only by storing more energy but also by changing the way energy is converted into motion. A glider sacrifices speed and maneuverability to obtain persistence. A powered AUV makes the opposite trade. Selecting between them therefore requires a clear understanding of whether the mission values rapid transit, precise track following, high-rate sensing, or long-duration coverage.

2.3. Unmanned Surface Vehicles

USVs benefit from an important physical advantage: the vehicle can communicate directly with satellites, terrestrial radio systems, and GNSS while carrying solar panels or other energy-harvesting equipment. The surface environment also allows radar, AIS, cameras, and other perception systems to be used without the severe attenuation that affects subsea sensing. A broad review of USVs identifies GNC, communications, sensing, reliability, and environmental disturbance as central challenges to fully autonomous operation [9],[10].

	AUV (Torpedo)	Seaglider	Slocum Glider	Spray Glider
Platform				
Propulsion Principle	Electric thruster (propeller) Active, continuous propulsion	Buoyancy-driven Pitch engine for glide control	Buoyancy-driven Pump-driven bladder for pitch	Buoyancy-driven Oil pump + movable mass for pitch
Endurance (Typical)	10 – 50+ hours (limited by battery capacity)	Months (2 – 12+ months) Very low power consumption	Months (3 – 12+ months) Very low power consumption	Months (6 – 12+ months) Very low power consumption
Speed (Typical)	2 – 6+ knots (1 – 3 m/s typical)	0.2 – 0.6 knots (0.1 – 0.3 m/s typical)	0.2 – 0.7 knots (0.1 – 0.35 m/s typical)	0.3 – 1.0 knots (0.15 – 0.5 m/s typical)
Payload Capacity	High (50 – 200+ kg) Flexible, modular payload bay	Low – Moderate (~5 – 20 kg)	Low – Moderate (~5 – 20 kg)	Moderate (10 – 30 kg) Higher volume than other gliders
Operating Depth	Up to 1,000 – 6,000+ m (Depth-rated by vehicle class)	Up to ~1,000 m	Up to ~1,000 m	Up to ~2,000 m
Key Characteristics				
- Actively propelled, highly maneuverable - Higher speed and payload capacity - Suitable for surveys, inspection, intervention, and complex missions - Energy-limited endurance - Extremely energy efficient - Long-duration, low-speed missions - Best for adaptive sampling and oceanographic monitoring - Limited payload and speed - Proven, robust, and widely used - Simple and reliable design - Long endurance for environmental monitoring and data collection - Limited payload and speed - Higher speed and deeper capability than traditional gliders - Larger payload volume - Efficient for extended missions in dynamic ocean environments				

Figure 2. Comparison of AUV and glider configurations.

Surface platforms can be optimized either for high speed or persistence. A fast survey USV may use conventional electric or combustion propulsion, whereas a long-duration observation vehicle can exploit wind, waves, and solar energy. Saildrone is a clear example of the latter approach. Field deployments have demonstrated the ability to carry a substantial oceanographic sensor suite over long routes while using wind propulsion and solar electricity [11].

Wave Glider takes a different approach by converting wave motion into propulsion while using solar power for electrical loads. Engineering sea trials demonstrated the practicality of wave-powered autonomous operation under varied ocean conditions [12]. These platforms show that the surface vehicle is not merely a smaller autonomous ship; it can be designed around an entirely different energy economy.

2.4. Hybrid, Cooperative and System-of-Systems Architectures

The next stage of AMS development is likely to involve multiple vehicle types operating as a

coordinated system. A USV can serve as a communication gateway for submerged AUVs. A surface platform can provide GNSS corrections, store large datasets, and act as a recovery or charging node. AUVs can perform high-resolution surveys while gliders provide persistent background measurements. Seabed stations can provide fixed acoustic references or charging interfaces.

Collaborative AUV research already shows that teams can combine localization, communication, and mission execution to achieve tasks that would be inefficient for a single vehicle [13]. The engineering challenge is that system-level performance is now governed by the weakest link. A fleet with excellent vehicles can still fail if communication is unreliable, if vehicles cannot maintain relative position, or if the energy-management strategy does not account for the fleet as a whole.

Table 2. Representative platform classes and engineering trade-offs

Platform	Primary environment	Strength	Principal limitation	Typical mission
AUV	Subsea	Precise survey and inspection	Finite stored energy	Mapping, inspection, MCM
Glider	Subsea	Very long endurance	Low speed and limited maneuverability	Ocean observation
USV	Surface	GNSS, communications and harvesting	Sea-state exposure	Survey and persistent monitoring
Hybrid	Surface/subsea	Flexible access and gateway capability	Mechanical and control complexity	Multi-domain inspection
Cooperative fleet	Multiple domains	Coverage, redundancy and task sharing	Coordination and network dependence	Distributed sensing

3. Key Engineering Subsystems

3.1. Hull Design and Hydrodynamics

Hull geometry establishes the baseline for drag, stability, maneuverability, internal packaging, pressure capability, and payload accessibility. In a propeller-driven AUV, hydrodynamic drag directly affects propulsion power. The engineering problem is therefore to achieve the required volume and structural strength with the smallest practical resistance while preserving stable and controllable motion. Fossen's marine-craft framework emphasizes the coupling between rigid-body dynamics, hydrodynamic forces, hydrostatics, and control-system design [14].

Torpedo-like hulls remain common because they provide a useful compromise between low drag, internal volume, and directional stability. However, a single optimum profile does not exist. A vehicle carrying a large forward-looking sonar, a wide optical field of view, or a hovering inspection payload may require a different geometry. Similarly, a deep-rated pressure hull may impose structural constraints that outweigh small hydrodynamic gains.

For a vehicle moving at speed V , the approximate drag power requirement is governed by the product of drag force and velocity. If drag is expressed as $D = 0.5 \rho V^2 S C_D$, then the ideal drag power is $P_D = D V = 0.5 \rho V^3 S C_D$. The cubic dependence on speed is especially important for endurance planning. A modest increase in cruise speed can produce a disproportionately large increase in propulsion power. This is why survey vehicles often operate at moderate speeds even

when their thrusters can provide much higher velocity.

Figure 3 compares four representative hull configurations considered in the hydrodynamic design of autonomous underwater vehicles (AUVs)—torpedo, Myring, spindle, and hybrid forms—and illustrates the principal geometric parameters of the Myring profile. Hull geometry has a direct influence on hydrodynamic drag, internal volume, stability, maneuverability, payload integration, and consequently the energy required to accomplish an autonomous mission. The torpedo configuration provides a relatively simple and streamlined arrangement, whereas the spindle-type form can achieve a highly streamlined geometry with potentially low hydrodynamic resistance but may provide less useful internal volume for equipment and payloads. The Myring configuration provides a practical compromise by incorporating a forebody, a parallel midbody, and an afterbody, thereby providing sufficient internal space for batteries, electronics, sensors, and other mission payloads while maintaining a hydrodynamically efficient external shape. As shown in the lower part of Figure 3, the overall Myring geometry can be described by the parameters aa , bb , cc , DD , nn , and θ (theta), representing the characteristic lengths, maximum diameter, curvature parameter, and stern taper angle, respectively. These parameters provide design variables through which the hull profile can be modified according to the required operating speed, payload volume, maneuverability, structural requirements, and mission endurance. Hybrid configurations provide an additional degree of design freedom by combining characteristics of

different hull forms. Therefore, hull-form selection should be regarded as a mission-driven multidisciplinary optimization problem, in which hydrodynamic efficiency must be balanced against payload capacity, structural integrity, propulsion

requirements, energy consumption, and operational functionality.

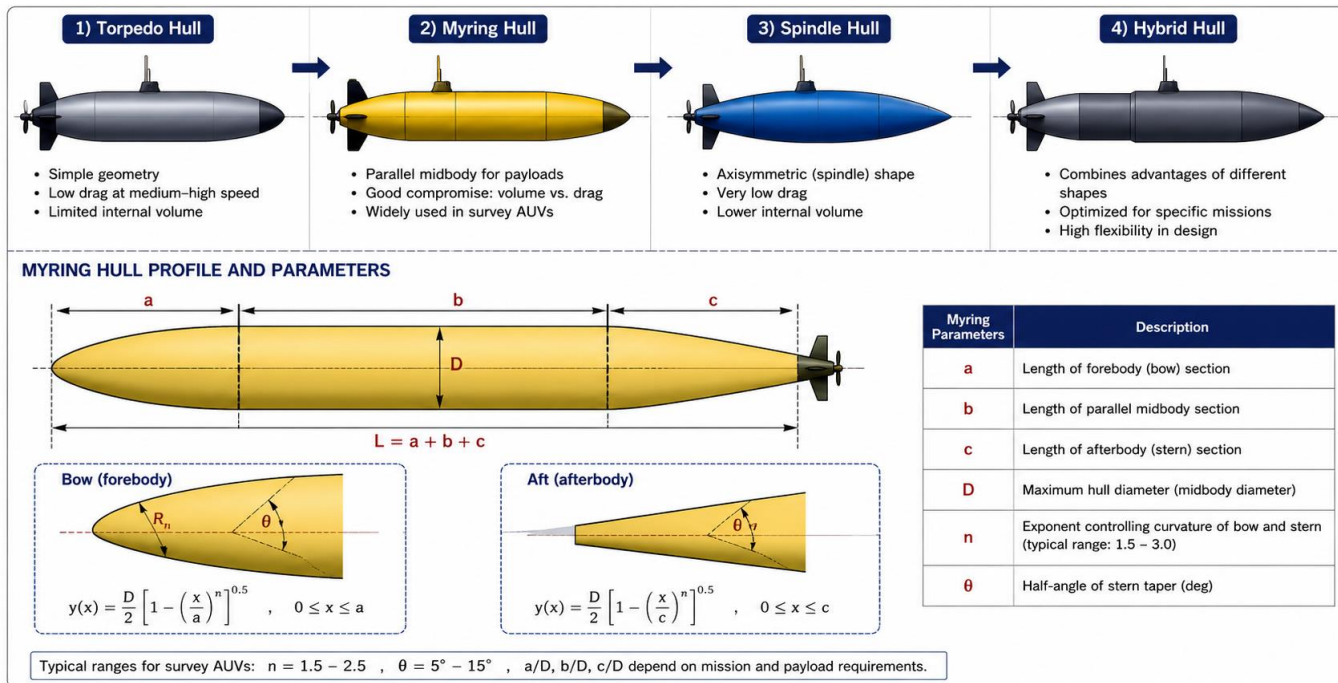


Figure 3. AUV hull-design comparison and Myring-type profile.

Appendages can also dominate local flow behavior. Fins, thruster mounts, sonar fairings, antenna housings, and sensor windows disturb the boundary layer and may create additional drag or noise. For sonar vehicles, vibration and acoustic self-noise can be as important as hydrodynamic resistance. Propeller selection must therefore consider not only thrust efficiency but also cavitation, blade-rate noise, structural vibration, and interference with sonar transducers.

3.2. Structural Materials and Deep-Water Packaging

Marine materials must satisfy several competing requirements: strength, corrosion resistance, mass, pressure tolerance, manufacturability, electrical isolation, thermal behavior, and lifecycle cost. Aluminum alloys remain attractive for moderate-depth vehicles because they are relatively light and easy to machine. Titanium is especially attractive for deeper systems because of its high specific strength and corrosion resistance, although cost and

fabrication requirements are higher. Composites offer high stiffness-to-weight ratios and can be useful for fairings and selected pressure structures, but their behavior under external pressure, moisture, impact, and repeated cycling requires qualification.

Deep-water design must be treated as a system problem. Pressure housings, penetrators, connectors, battery containers, buoyancy materials, optical windows, and sensor interfaces all experience the external pressure environment. A failure in one component can compromise the entire vehicle. The design process should therefore use depth-rated qualification tests, pressure cycling, leak testing, and conservative failure margins. Materials that perform well in laboratory air tests may behave differently after prolonged exposure to seawater and repeated pressure cycles.

Table 3. Comparison of common AMS structural materials

Material class	Advantages	Limitations	Typical engineering use
Aluminum alloys	Low density, machinability, moderate cost	Corrosion control and galvanic compatibility	Frames and moderate-depth housings
Titanium alloys	High specific strength, corrosion resistance	High cost and demanding fabrication	Deep-water pressure housings and critical structures
Stainless steels	High strength, mature fabrication	Higher density and corrosion considerations	Frames, shafts and fittings
Composites	Low mass and tailored stiffness	Pressure/impact qualification and moisture effects	Fairings and selected shells
Syntactic foams	High buoyancy at depth	Cost and damage sensitivity	Deep-water buoyancy modules

3.3. Propulsion and Power Systems

Propulsion is one of the strongest links between mechanical engineering and autonomy. The vehicle cannot execute an intelligent mission if its propulsion system cannot provide sufficient thrust to overcome drag, currents, or sea-state disturbances. For AUVs, electric motors driving fixed or controllable propellers dominate because they are compact, efficient, controllable, and compatible with sealed pressure-tolerant systems. USVs provide a broader design space that includes electric thrusters, diesel-electric arrangements, combustion engines, wind propulsion, and wave propulsion.

The useful propulsive power can be approximated as $P_u = T V$, where T is thrust and V is forward speed. Electrical power is higher because of propeller, motor, drive, and transmission losses. If the combined efficiency is η , then $P_e = TV/\eta$. This simple expression shows why efficiency improvements have compounding benefits. Reducing drag lowers required thrust; improving propeller efficiency lowers electrical power; and reducing power consumption extends endurance or allows more energy to be allocated to payloads.

Modern AUV power systems are dominated by rechargeable lithium-ion batteries because of their combination of energy density, efficiency, maturity, and availability. However, battery safety, thermal management, pressure tolerance, charge balancing, isolation, and emergency shutdown

must be engineered as part of the propulsion architecture. A battery pack should not be treated as a passive energy tank; it is an active safety-critical subsystem.

Fuel cells remain attractive for larger vehicles requiring long endurance. Earlier assessments identified the limited specific energy of conventional batteries as a principal barrier and examined proton-exchange-membrane fuel cells, reactant storage, and hybrid battery/fuel-cell architectures [15]. Later design guidelines showed that fuel-cell integration requires simultaneous consideration of stored hydrogen and oxygen, system volume, thermal management, and AUV design parameters [16]. More recent reviews continue to identify hydrogen fuel cells as a promising route to high-energy long-duration underwater operation, especially for large-class vehicles [17].

3.4. Energy Harvesting and Long-Endurance Operation

The engineering objective for long-duration AMS should be energy-aware autonomy rather than simply larger batteries. The mission energy budget contains propulsion, payload sensors, computing, navigation, communication, thermal management, hotel loads, and reserve energy. A useful first-order expression is:

$$E_{mission} = E_{prop} + E_{payload} + E_{compute} + E_{nav} + E_{comm} + E_{hotel} + E_{reserve}.$$

The reserve term is particularly important because an autonomous vehicle must retain enough energy

to abort, surface, reach a rendezvous point, or complete recovery procedures.

Table 4. Energy storage and power technologies

Technology	Main benefit	Main engineering limitation	Best-fit application
Li-ion battery	High practical energy density and mature supply chain	Thermal safety, finite stored energy	Most electric AUVs
Pressure-tolerant Li-polymer	Reduced pressure-housing burden	Packaging and safety qualification	Selected deep AUVs
PEM fuel cell	High mission energy and quiet operation	Reactant storage, heat/water management	Large long-endurance AUVs
Solar electrical	Renewable surface power	Weather, area and orientation dependence	Persistent USVs
Wave propulsion	Very low direct propulsion energy demand	Dependence on sea state and mechanical complexity	Persistent USVs
Hybrid battery + harvesting	Improved persistence and resilience	System complexity and control	Long-duration systems

Wave energy harvesting is attractive because surface platforms continuously experience mechanical excitation. A review of in-situ wave energy harvesting for unmanned marine devices classifies external and internal approaches and highlights the potential of using environmental motion to supplement or replace stored energy [18]. More recent work extends this concept toward hybrid wave-energy systems designed around actual unmanned-ocean mission requirements and lifecycle durability [19].

Solar energy is easier to integrate than wave energy but is limited by available deck area, weather, latitude, fouling, and payload demand. For a surface vehicle, solar power can be used directly for electronics and batteries while wind or wave energy supplies propulsion. This separation of energy functions can be highly effective because electrical loads are relatively predictable while propulsion demand varies with speed and sea state.

Thermal energy is particularly interesting for gliders. The Slocum thermal engine showed that an ocean temperature gradient can be converted into mechanical work [5]. The energy flux available from the environment is small, but gliders are designed to operate with very low average power. The engineering lesson is broader than the specific

device: a low-power vehicle architecture can make a weak environmental energy source useful.

Figure 4 presents an AMS-adapted energy architecture for long-endurance Autonomous Marine Systems (AMS), illustrating the integration of onboard energy generation, energy management, storage, distribution, power consumption, monitoring, and energy replenishment. The architecture is based on the principle that endurance cannot be improved solely by increasing battery capacity; rather, the complete energy chain must be considered as an integrated system. Solar, wave, thermal, and fuel-cell technologies are shown as potential complementary energy sources that can supplement the primary energy-storage system and reduce dependence on finite onboard battery capacity. The Energy Management System (EMS) coordinates these sources with the battery and onboard loads by monitoring available energy, regulating power conversion, optimizing energy allocation, and maintaining appropriate reserves for critical mission functions. The stored energy is distributed among the major power consumers, including propulsion, sensors and mission payloads, onboard computing, and communication systems. Because these loads have substantially different power requirements and operating

profiles, intelligent energy management can schedule non-critical functions, adapt sensor and communication activity, and modify vehicle operating conditions according to the remaining energy budget. The architecture also incorporates energy monitoring and diagnostics, including battery state-of-charge, state-of-health, power-flow monitoring, and fault detection, which are essential for reliable long-duration autonomous operation. At the infrastructure level, docking and charging stations provide an additional mechanism for energy replenishment and can simultaneously support autonomous docking, high-rate charging,

data transfer, health assessment, software updating, and mission reconfiguration. Alternative replenishment approaches, such as charging from a surface vessel or other mobile infrastructure, can further extend operational flexibility. Consequently, the architecture demonstrates a transition from conventional battery-limited autonomy toward energy-aware autonomy, in which energy availability, mission objectives, environmental conditions, vehicle health, and payload requirements are continuously considered in determining the most efficient operating strategy.

Integrated Generation – Management – Storage – Distribution – Replenishment

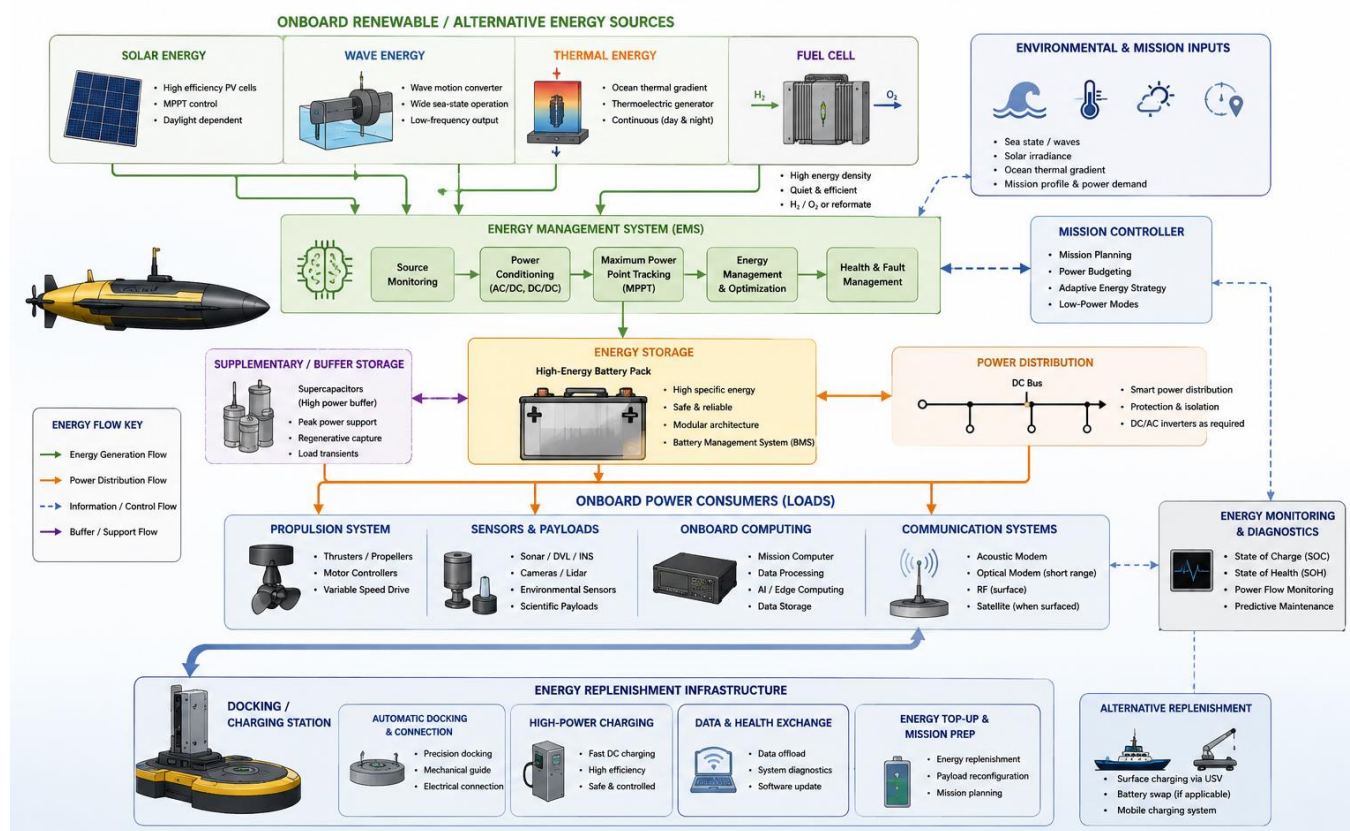


Figure 4. Energy architecture for long-endurance AMS.

3.5. Guidance, Navigation and Control

GNC is the subsystem that converts mission intent into reliable vehicle motion. It includes guidance logic, state estimation, feedback control, actuator allocation, fault detection, and mission-level behaviors. In underwater operation, the absence of GNSS forces the system to estimate position from indirect information. Classical AUV navigation approaches include dead reckoning, acoustic

positioning, terrain-relative navigation, map matching, and integrated sensor fusion [20–21].

Dead reckoning is simple and high-rate but accumulates error. DVL can reduce velocity uncertainty when bottom lock or water-track measurements are available. Acoustic systems such as USBL and LBL can provide external position references but require transponders or a support system. Terrain-relative navigation and

bathymetric matching can provide long-range correction where seabed maps are available. Visual or sonar SLAM can support local mapping, although turbidity, low texture, moving targets, and computational load complicate deployment.

Recent work on underwater SLAM emphasizes the value of fusing proprioceptive sensors such as IMUs and DVLs with exteroceptive sensors such as cameras, sonar, and LiDAR [22]. The engineering priority is not to select one perfect sensor but to construct a navigation architecture that degrades gracefully when a sensor becomes unavailable. A high-integrity system should know when its navigation estimate is becoming unreliable and should change its mission behavior accordingly.

Guidance and control must also account for ocean currents. The shortest geometric path is not necessarily the lowest-energy path. A vehicle may save energy by allowing a favorable current to carry it along part of a mission, even if this increases the geometric distance. Energy-aware path planning therefore couples hydrodynamics, current prediction, vehicle dynamics, and navigation uncertainty. Reviews of AUV path planning show the increasing importance of dynamic environments, energy cost, obstacle avoidance, and multiple-vehicle coordination [23–24].

3.6. Sensor Systems and Payload Integration

An autonomous vehicle has value only if it produces useful information or performs a physical task. Sensor selection is therefore a mission-design decision. Typical payloads include multibeam echo sounders, side-scan sonar, synthetic aperture sonar, sub-bottom profilers, CTD sensors, ADCPs, cameras, laser scanners, magnetometers, hydrophones, and chemical or biological sensors. A recent review of underwater sensing technologies emphasizes that sensor choice must be linked to the intended observation, platform constraints, and environmental conditions [25].

Payload integration is a systems-engineering problem. A sonar may require low vibration and a clean acoustic field; a camera may require lighting and a clear optical window; a magnetometer may need separation from motors and ferromagnetic structures; and an ADCP requires an unobstructed acoustic path. Electrical noise, heat, timing

synchronization, data storage, and computational bandwidth also matter. Adding a sensor therefore has consequences beyond its own mass and power rating.

A useful design approach is to divide payloads into mission-critical, mission-enhancing, and opportunistic categories. Mission-critical sensors receive guaranteed power, data bandwidth, mounting quality, and navigation support. Mission-enhancing sensors operate when energy and data budgets permit. Opportunistic sensors may be activated only under specific environmental conditions. This approach allows the autonomy layer to schedule sensors according to mission value rather than running every instrument continuously.

Figure 5 illustrates an integrated Guidance, Navigation, and Control (GNC) architecture for an Autonomous Underwater Vehicle (AUV), in which mission-level objectives are progressively translated into vehicle motion commands and closed-loop propulsion actions. The Mission Planner defines the overall mission objectives, waypoints, operational constraints, and task sequence, while the Guidance module converts these high-level requirements into feasible reference trajectories, velocities, depths, headings, or other vehicle states. The Controller then compares the desired states with the estimated vehicle states and generates appropriate control commands for the propulsion and actuation system. Reliable feedback is essential throughout this process because underwater vehicles operate in an environment where external positioning references are intermittent and hydrodynamic disturbances can significantly affect vehicle motion. The navigation subsystem therefore integrates measurements from the Inertial Navigation System (INS), Doppler Velocity Log (DVL), depth sensor, compass, acoustic positioning systems, and terrain-navigation sensors to estimate the vehicle's position, velocity, attitude, and depth. Sensor fusion can compensate for the individual limitations of these sensors; for example, INS provides high-rate motion information but accumulates drift over time, whereas DVL can provide velocity measurements relative to the seabed when bottom lock is available, and acoustic

positioning can provide absolute or relative position corrections over longer spatial scales. Terrain-based navigation can provide an additional source of positional information in environments where acoustic infrastructure or satellite-based positioning is unavailable. The resulting state estimate is continuously fed back to the guidance and control loops, allowing the AUV to compensate for disturbances, maintain the desired trajectory,

and adapt its behavior during mission execution. The architecture therefore represents GNC as an integrated closed-loop engineering system rather than as independent navigation, guidance, and control functions, with the quality of state estimation directly influencing trajectory accuracy, energy consumption, maneuverability, mission reliability, and ultimately the autonomy of the vehicle.

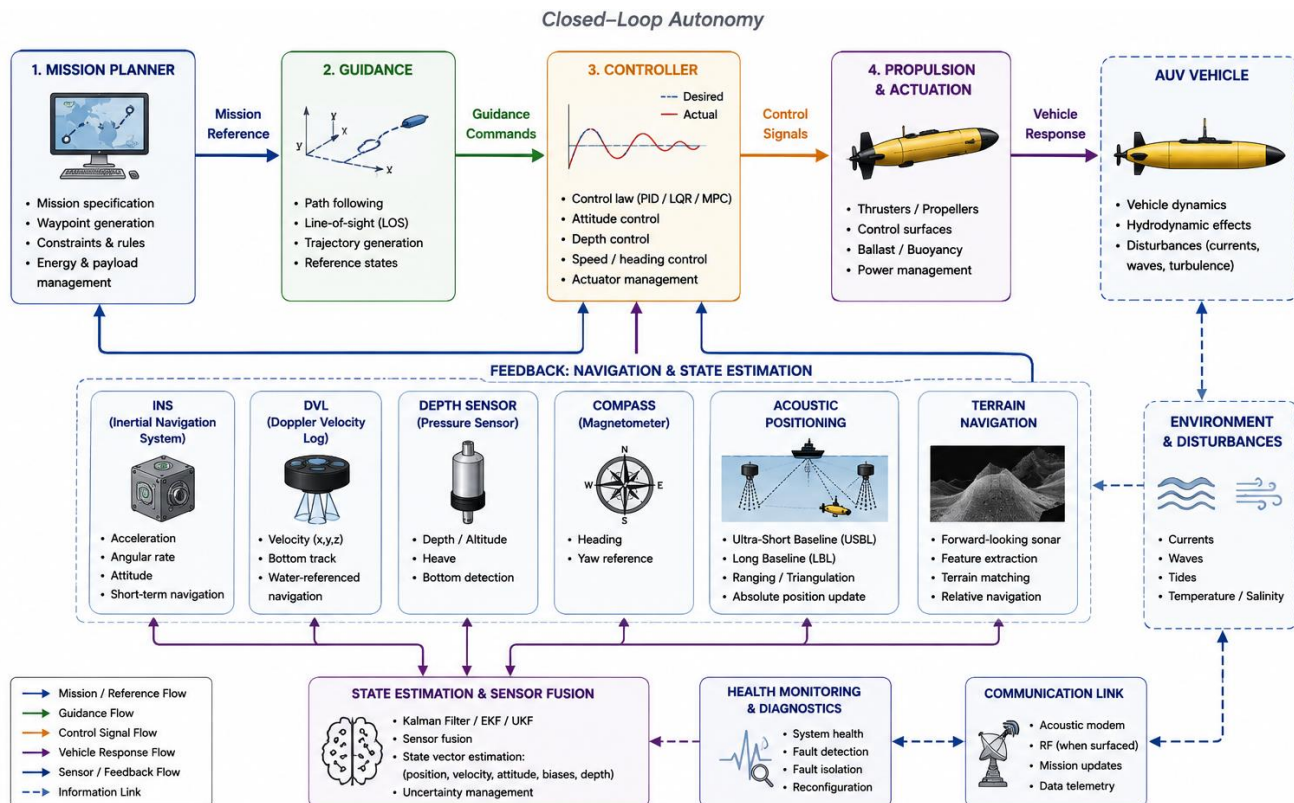


Figure 5. Integrated AUV GNC architecture.

3.7. Communication Systems

Communication is one of the most difficult subsystems in underwater autonomy. Radio-frequency signals attenuate strongly in seawater, leaving acoustic communication as the most practical long-range wireless method for many missions. Acoustic links can provide command, status, positioning, and low-rate data, but they suffer from limited bandwidth, propagation delay, multipath, Doppler effects, and environmental variability [26–27].

The underwater acoustic channel is unusual because it combines characteristics that are individually difficult: low link quality, long propagation delay, strong multipath, and motion-dependent Doppler distortion. Recent reviews describe it as one of the most challenging wireless media in practical use [27]. For an autonomous vehicle, the consequence is that communication cannot be treated as an always-available control link. Mission logic must remain safe when communication is absent for minutes or hours.

Table 5. Common AMS sensors and practical integration concerns

Sensor	Primary output	Typical application	Key integration issue
Multibeam sonar	Bathymetry	Seabed mapping	Navigation and motion compensation
Side-scan/SAS	Acoustic imagery	Inspection and target detection	Vehicle stability and self-noise
CTD	Conductivity, temperature, depth	Oceanography	Flow exposure and calibration
ADCP/DVL	Velocity/current	Navigation and oceanography	Bottom lock and acoustic interference
Camera	Optical imagery	Inspection and identification	Lighting and turbidity
Magnetometer	Magnetic field	Cable/target detection	Vehicle magnetic signature
Hydrophone	Acoustic field	Monitoring and detection	Propulsion self-noise

Optical communication provides a complementary approach. Blue-green optical wavelengths experience relatively favorable transmission windows in seawater, and optical links can support much higher data rates and lower latency than acoustic systems [28–29]. The penalty is range and alignment. Absorption and scattering limit distance, while turbidity, bubbles, vehicle motion, and pointing errors can interrupt the link. Practical reviews therefore emphasize channel characterization, pointing-acquisition-tracking, modulation, and network design [30–31].

The most credible architecture is hybrid. Acoustic communication can maintain long-range low-rate connectivity; optical communication can transfer high-volume sonar or image data when vehicles are close and aligned; and RF or satellite communication can be used when a vehicle reaches the surface or communicates through a buoy or USV gateway. Hybrid architectures also create opportunities for edge computing: instead of transmitting raw sonar data through a low-bandwidth acoustic link, the vehicle can process the data locally and transmit only detections, compressed products, or mission updates.

Figure 6 illustrates a hybrid communication architecture for Autonomous Marine Systems (AMS) in which different communication technologies are integrated according to their respective range, bandwidth, latency, and environmental limitations. At the surface, a USV or communication buoy acts as a gateway between the submerged autonomous vehicles and the shore

control center, using RF or satellite communication to provide long-range connectivity for mission planning, fleet supervision, data transfer, and software updates. Beneath the surface, acoustic communication provides the primary long-range link between the gateway and AUVs because acoustic signals can propagate over substantially greater distances in seawater than optical signals; however, its relatively limited bandwidth makes it more appropriate for command, control, telemetry, and navigation-related information than for transferring large datasets. The AUVs can additionally establish short-range optical links with neighboring vehicles and with a subsea docking/charging station. These optical links can provide high-rate data transfer when suitable line-of-sight and water-quality conditions are available, making them particularly attractive for transferring sonar, imaging, mapping, and other high-volume sensor data. The docking station further provides an opportunity for battery charging, vehicle health assessment, payload data transfer, and mission preparation before redeployment. Consequently, the architecture combines RF/satellite, acoustic, and optical communication as complementary rather than competing technologies, providing a potentially more resilient communication framework for long-duration and cooperative AMS missions. Such a multi-layer architecture is particularly relevant to future autonomous fleets, where reliable low-rate connectivity can be maintained over long distances while high-rate optical communication is employed opportunistically when vehicles approach one another or a subsea infrastructure node. This

approach can therefore help address one of the fundamental limitations of underwater autonomy: the simultaneous need for long-range connectivity, high data throughput, low latency, and operational robustness.

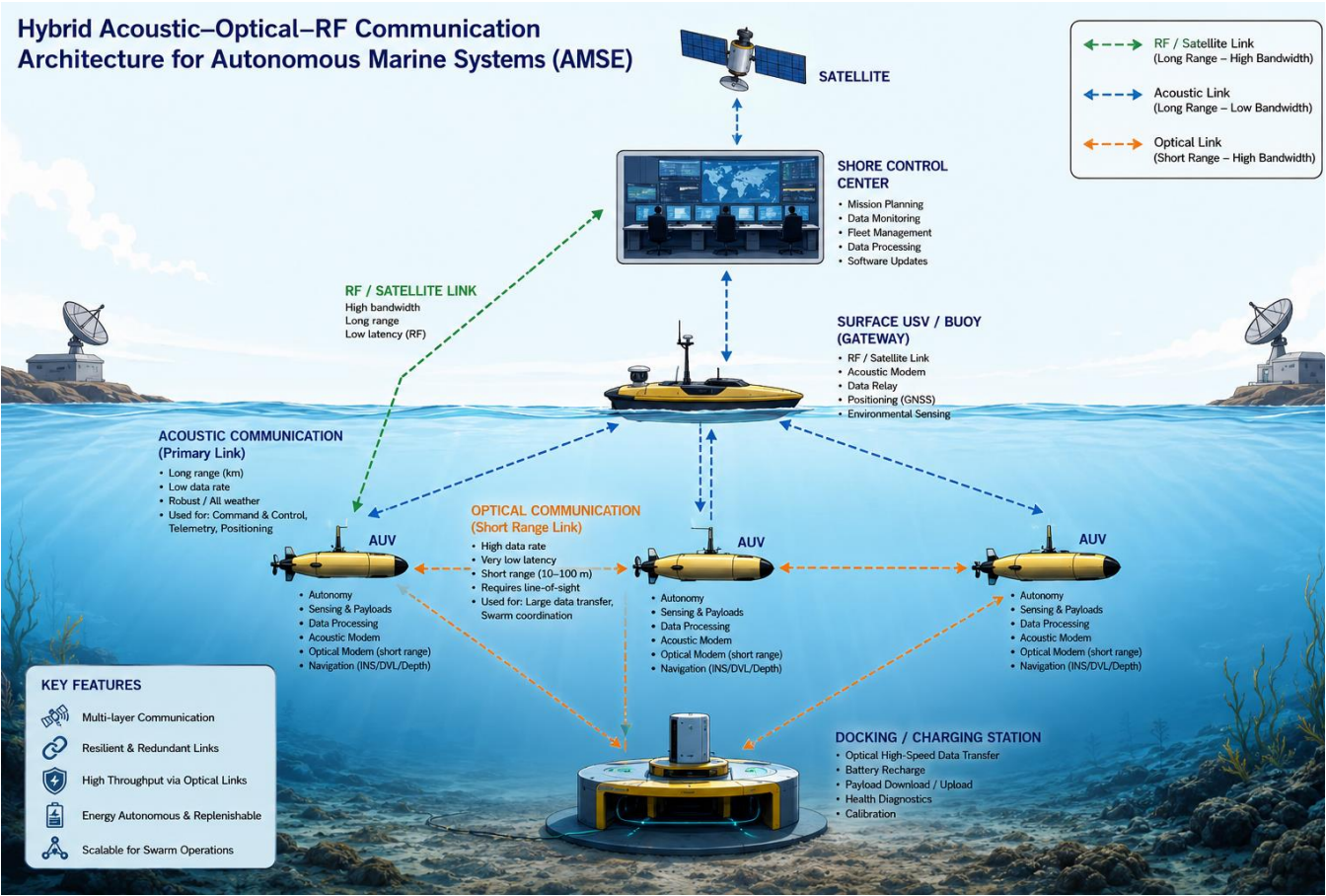


Figure 6. Hybrid acoustic–optical–surface communication architecture.

Table 6. Underwater communication technologies

Technology	Typical role	Strength	Principal limitation
Acoustic	Long-range subsea command/status	Best practical underwater range	Low bandwidth and latency
Optical	Short-range high-volume transfer	Very high data rate and low latency	Alignment, turbidity and range
RF	Very short range underwater / surface	Simple where applicable	Strong seawater attenuation
Satellite	Surface-to-shore connectivity	Global reach	Requires surfacing/antenna access and energy
Hybrid	Adaptive mission networking	Balances range and throughput	More complex architecture

4. Benefits of Autonomous Marine Systems

4.1. Safety and Personnel Exposure

Safety is the most immediate operational benefit of autonomous marine systems. AUVs can conduct surveys near subsea structures, in contaminated waters, beneath ice, at extreme depths, or in conditions that expose divers and crewed vessels to greater risk. Removing personnel from the immediate hazard zone does not remove operational risk, but it changes the risk profile by reducing direct exposure and the number of high-risk close-proximity tasks.

Launch and recovery are often overlooked in discussions of autonomy. A vehicle that is autonomous during its mission may still require significant deck work before and after deployment. Engineering a safe launch and recovery system can therefore be as important as improving autonomy algorithms. REMUS operations illustrate the value of compact vehicles and purpose-designed launch/recovery arrangements, while larger deep-water systems require dedicated handling equipment and trained operators [32–33].

4.2. Cost and Operational Productivity

Autonomy does not automatically mean low cost. Vehicles require batteries, maintenance, software support, deployment vessels, skilled technicians, communication infrastructure, and recovery operations. The economic benefit appears when autonomy changes the number of support hours required per unit of useful data. A persistent platform can replace repeated vessel visits, while a compact AUV can survey an area without keeping a large vessel continuously on station.

The cost argument is strongest for repetitive tasks. Hydrographic survey, pipeline inspection, cable route monitoring, environmental compliance, and long-duration ocean observation all benefit from standardized missions. Once the mission has been validated, software-defined repeatability can reduce variability between deployments and make the resulting data easier to compare over time.

4.3. Data Quality and Coverage

Autonomous platforms can provide consistent sensor geometry, repeatable tracks, and high temporal sampling. This is particularly valuable for change detection. Instead of collecting a single

survey every few years, an autonomous system can repeat the same route at shorter intervals and identify changes in seabed morphology, infrastructure condition, or environmental parameters. Gliders have demonstrated this value at oceanographic scales by repeatedly sampling the water column over long periods [4,8].

4.4. Environmental and Commercial Benefits

Smaller autonomous platforms can reduce the need for large support vessels, which may lower fuel use and emissions for some missions. Renewable-energy surface platforms provide an even stronger example. SAILDRONE combines wind propulsion and solar electrical generation [11], while Wave Glider uses wave energy for propulsion [12]. These architectures are particularly attractive when persistence is more important than speed.

Commercial opportunities extend beyond traditional oceanographic research. AMS can support offshore wind development, subsea cable and pipeline inspection, hydrographic survey, fisheries monitoring, environmental compliance, port security, maritime surveillance, search operations, and infrastructure condition assessment. The commercial model is gradually shifting from selling vehicles to selling data, inspection results, availability, and persistent monitoring as services.

5. Conclusion

Autonomous Marine Systems have progressed from experimental autonomous vehicles toward increasingly capable engineering platforms that can perform persistent observation, survey, inspection, and environmental missions. The evolution from early AUVs to modern gliders, USVs, hybrid vehicles, and cooperative systems demonstrates that no single architecture is optimal for every marine task. Platform selection must instead be driven by the required combination of speed, endurance, payload, depth, maneuverability, deployment constraints, and mission data quality.

The engineering subsystems reviewed in this paper are strongly coupled. Hull geometry influences drag and therefore propulsion power; propulsion and energy storage determine achievable endurance; sensor and payload integration affects both information quality and power demand;

navigation and GNC determine trajectory accuracy; and communication architecture determines how mission information can be exchanged. These interactions mean that optimizing an individual subsystem without considering the complete vehicle can produce a technically successful but operationally inefficient system.

The principal benefits of AMS arise when this integrated engineering architecture is matched to missions that are repetitive, spatially distributed, hazardous, remote, or difficult to support continuously with crewed assets. Reduced

personnel exposure, repeatable measurements, persistent coverage, and reduced dependence on support vessels can create substantial operational value. Future development should therefore emphasize modular vehicle architectures, energy-efficient propulsion, robust navigation, integrated payload interfaces, and communication systems designed around the actual information needs of the mission. These foundations provide the basis for addressing the persistent engineering challenges, emerging technologies, and lifecycle strategies considered in the companion paper.

Table 7. Summary of major AMS benefits

Benefit	Engineering mechanism	Operational value
Personnel safety	Remote operation of hazardous tasks	Lower direct exposure
Cost efficiency	Reduced ship time and repeatable missions	Lower recurring monitoring cost
Persistence	Long endurance and environmental energy	Higher temporal coverage
Data consistency	Repeatable tracks and sensor geometry	Improved change detection
Access	Small/deep vehicles reach difficult areas	New survey and inspection capability
Environmental performance	Wind/wave/solar energy and smaller support footprint	Potentially lower emissions
Commercial scalability	Software-defined and repeatable missions	New data and monitoring services

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