MINION:
Modular and Independent Navigational Intelligent Orientable Nozzle-Thruster

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Synopsis

The MINION concept, standing for Modular Independent Navigational Intelligent Orientable Nozzle-Thruster, encapsulates a modular propulsion unit designed for Unmanned Marine Vehicles (UMVs) with power, communication, computing power, sensors (GNSS, IMU), and directional thrust within a compact, watertight module. In other words the MINION concept posits that a modular directional thruster can work as a simple robotic vehicle, being equipped with all the sub-systems required to do it. Sets of MINION units can be suitably connected through mechanical frames and/or hulls to constitute different shape UMVs.

The propulsion system is designed for UMV applications requiring modularity, redundancy, and independence, enhancing portability, design flexibility, and cable elimination. MINION operates using a mixed-flow or centrifugal pump, achieving precise 360° thrust control through a steerable nozzle, thereby optimizing maneuverability in marine environments. When integrated into an Autonomous Surface Vehicle (ASV), MINION functions as a propulsion and steering unit, computing element, navigation sensor package, and energy source, offering protection during bottom collisions. Moreover, the MINION architecture is designed to facilitate automated adherence to FAIR (Findable, Accessible, Interoperable, Reusable) data principles. This includes the promotion of standardized variable naming conventions, thereby enhancing the interoperability and reusability of data generated by marine robotic systems.

Keywords: Thruster; Pump-Jet; ASV; USV; Modular; Dynamic Positioning

1 Introduction

Oceans, covering 71% of the Earth's surface, play a crucial role in regulating climate, supporting economies, and sustaining life. They act as carbon sinks, absorbing one-third of CO_2 emissions since the Industrial Revolution through marine processes such as *blue carbon* (Macreadie et al., 2019). Industries such as fisheries, shipping and energy depend on oceans, making sustainable management vital. Oceans influence climate patterns, generate half of the oxygen on Earth, and affect global weather systems. However, rising sea levels and extreme weather events due to climate change threaten coastal ecosystems and human settlements (Church et al., 2013; Antonioli et al., 2017).

Unmanned Surface Vehicles (USVs) offer a cost-effective solution to monitor ocean environments. Unlike traditional marine survey methods, USVs provide advantages in time efficiency, coverage, and resilience in extreme conditions (Bruzzone et al., 2020). They are deployed for environmental monitoring, hydrological exploration, search and rescue, and military applications such as antisubmarine operations. USVs also facilitate research in autonomous technologies such as navigation algorithms (Xing et al., 2023), collision avoidance (Zaccone and Martelli, 2020), and berthing (Wu et al., 2024).

This paper introduces a novel modular propulsion system for USVs, called MINION—Modular Independent Navigational Intelligent Orientable Nozzle-Thruster. MINION integrates power, communication, intelligence, Global navigation satellite system (GNSS) receiver, Inertial Measurement Unit (IMU) sensors, and thrust directionality into a single, watertight unit. Developed under the project (Odetti et al., 2020c), MINION enhances the capabilities of the SWAMP (Shallow Water Autonomous Multipurpose Platform) class of Autonomous Surface Vehicles (ASVs), initially designed for wetland monitoring. Beyond this, the system supports research in hydrodynamics (Pellegrini et al., 2023), propulsion (Odetti et al., 2019), and marine robotics (Odetti et al., 2020b). Its modular design offers flexibility and scalability, addressing various marine engineering challenges while contributing to the broader goal of improving marine technology.

Authors' Biographies

Angelo Odetti 0000-0003-0338-0742 Graduated in Naval Architecture and Marine Engineering in 2010 and earned a Ph.D. in 2020 from the University of Genoa. Since 2011, he has led the design of a second-gen hovercraft in FP-7 Hoverspill and patented new technologies. Joining CNR-INM in 2013, he has worked on EU and national projects, currently coordinating the PRIN MARMOT project and PNRR projects tasks. His research focuses on vehicles for remote and hazardous areas, including the ASV SWAMP. He has participated in polar scientific campaigns.

Massimo Caccia 0000-0002-4482-4541 graduated in Electronic Engineering from the University of Genova in 1991. He directed CNR ISSIA from 2013 to 2018 and joined CNR in 1993, focusing on marine robotics. A pioneer in unmanned surface vehicles, he has over 200 publications. He coordinated projects like Interreg MATRAC-ACP, PON ARES, and EC Blue RoSES and participated in EC projects including FP7 MINOAS, CART, MORPH, CADDY, and H2020 EXCELLABUST.

Gabriele Bruzzone 0000-0002-9569-1160 graduated cum laude in electronic engineering from the University of Genoa in 1993. He has been with the CNR since 1996, becoming a senior researcher in 2010 and a director of research in 2023. Leading the Marine Robotics lab since 2009, he has developed various robotic vehicles, including USVs, ROVs, a USSV, and UGV. His robots have been used in scientific campaigns, including in the Arctic and Antarctic.

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2 Objectives

The primary scope of this paper is to introduce and validate the MINION propulsion system as a modular and autonomous solution for Unmanned Maritime Vehicles (UMV). The specific objectives and requiremetns we set out to achieve include the following:

- Enhanced Modularity and Flexibility: To design a propulsion unit that integrates key functions—power, communication, intelligence, and thrust—into a single compact, modular component, allowing for easy adaptation and integration with various UMV platforms.
- Improved Autonomy and reliability: To develop a system that supports advanced autonomous operations by incorporating onboard computing, navigation sensors, and wireless communication, thereby reducing the dependency on external systems and cables.
- Robust Performance also in Challenging Environments: To ensure that the propulsion system is capable of reliable operation in diverse and harsh marine environments, such as shallow waters, by utilizing a Pump-Jet principle for propulsion and thrust control.
- Integration and Data Management: To facilitate integration with existing marine robotics systems and adhere to FAIR data principles, enhancing data accessibility, interoperability, and usability across different research and operational contexts.

By fulfilling these requirements, the MINION system seeks to enhance the capabilities of UMVs, making them more adaptable, efficient, and applicable in various marine scenarios. The subsequent sections will illustrate how these goals are achieved through the design, implementation, and testing of the MINION propulsion unit.

3 State of the Art

MINION is a modular system that arises from the idea of creating a propulsion system engineered for various applications of unmanned Maritime Vehicle (UMV). The design principles of MINION are rooted in the imperative for modular, redundant, and independent systems, catering to exigencies such as robot portability, design flexibility, and cable removal. Functioning at a good level of autonomy, MINION establishes a paradigm in propulsion, integrating into UMV platforms.

Modularity (Chen and Liu, 2022) and interoperability are two critical keywords in the field of marine robotics. They ensure cost reduction, adaptability, and evolution throughout a system's life cycle. Modularity in marine robotics refers to the design and organization of systems into separate and interchangeable modules. According to Costanzi et al. (2020) this allows:

- Component Separation: Modularity involves breaking down a system into discrete components or modules. Each module performs a specific function and can be replaced or upgraded independently.
- Interchangeability: Modules are designed to be interchangeable. If one module fails or needs an upgrade, it can be swapped out without affecting the entire system.
- Cost Efficiency: Modularity reduces costs by allowing targeted maintenance and upgrades. It also facilitates adaptation to new technologies over the system's life cycle.
- Standardization: Open standards and architectures enhance modularity. Common interfaces and protocols enable seamless integration of different modules.

Modularity ensures flexibility, scalability, and efficient system management and for this reason ”Modular” has become an important keyword in robotics as shown in fig. 1 where a research made in SCOPUS shows a clear trend in the presence of this keyword in robotics research. For this reason especially AUVs are designed in a modular way with middle section expandable by predefined payload sections. Examples are MARES AUV (Cruz and Matos, 2008) or the Starfish AUV (Sangekar et al., 2008). The hybrid vehicles like e-URoPe (Odetti et al., 2017a) and the Ecorobotics vehicle P2-ROV (Odetti et al., 2017b), are built from predefined modules while vehicles like TriMARES (Ferreira et al., 2012), are built from existing vehicles (Ferreira et al., 2010). The recently published MUM-vehicle (Ritz et al., 2019) is a large scale AUV, modularly configured of predefined and customized modules for deep-sea operations.

Also modular control strategies are design to be adaptable to various USVs (Müller et al., 2020).

The seek of modularity brought, in the recent years, to reduce the size of vehicles keeping modularity as a key point (Yang et al., 2024; Paraschos and Papadakis, 2021) and to develop various modules (Falcão Carneiro et al., 2022; Gutiérrez-Flores and Bachmayer, 2022) In particular, Tolstonogov et al. (2020) proposed a module that consists of a cylindrical housing, two endcups with wireless power transfer system (Martínez de Alegría et al., 2024) in each

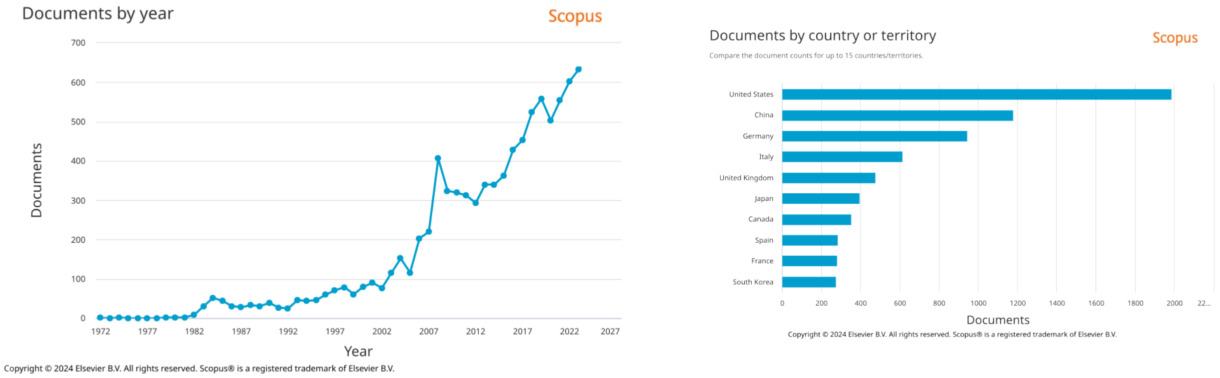


Figure 1: SCOPUS 2024 results of Advanced Search on *TITLE-ABS-KEY ("modular") AND TITLE-ABS-KEY ("robotics")*

of them, the battery pack with the single-board control computer inside. The authors used this module to create a vehicle that consists of various modules (Tolstonogov et al., 2021) and aims for long-term coastal monitoring.

Certainly! Here's the additional paragraph to include just after the introduction, addressing the specific requirements and objectives of the paper:

4 MINION description

MINION encapsulates a modular propulsion system that harmonizes Power, Communication, Intelligence, Sensoring (GNSS, IMU), Thrust, and Thrust Directionality within a singular compact and watertight element as shown in fig. 2 where it is shown that a MINION integrates a Pump-Jet thruster, motor controllers, 24V battery, Raspberry Pi 3b+, WiFi, GNSS, and IMU in a watertight enclosure. MINION is a full electric (24 V), small size (Diameter = 145 mm, Height = 500 mm, Weight = 3.1 kg) and low power (Max consumption = 240 W) module. It incorporates in one single watertight enclosure (shown in fig. 3): Thruster and Thrust Vectoring via Pump-Jet concept exploitation Odetti et al. (2019), Pump and Azimuth motor controllers, a 24V - 12 Ah li-ion battery and Voltage converters, Raspberry Pi 3b+ with digital and analog signals board with signal converters, WiFi module for communication, GNSS for positioning and IMU for attitude.

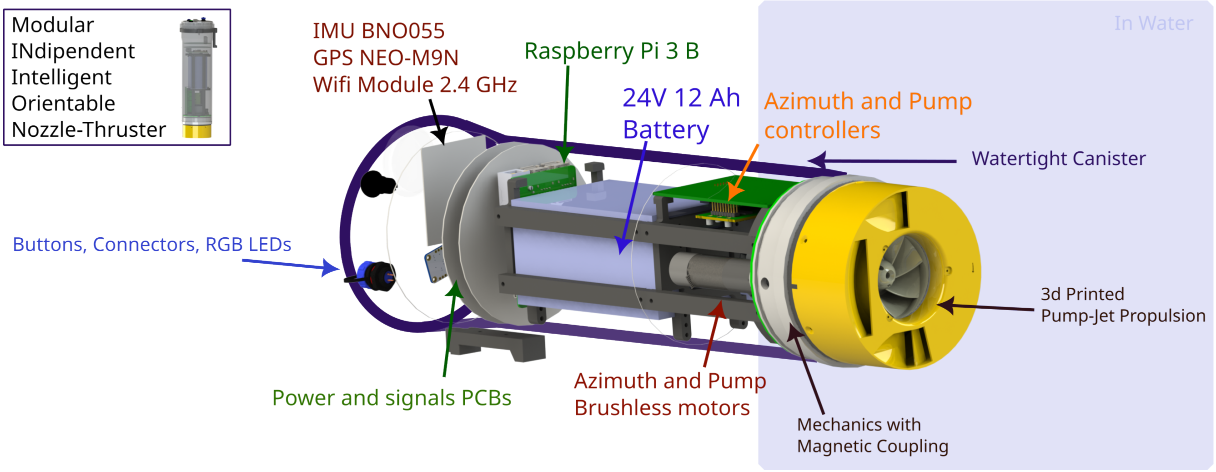


Figure 2: The MINION module overview

The operational mechanism of MINION relies on the Pump-Jet principle, rooted in a mixed-flow or centrifugal pump, inducing static pressure to propel water through a steerable nozzle. Characterized by 360° steering for enhanced maneuverability, a Pump-Jet thruster leverages the centrifugal pumps impeller action to generate high-pressure water, and by directing this pressurized water through a steerable nozzle, it achieves thrust and control for effective maneuverable propulsion in shallow water marine environments. When assimilated onto an Autonomous Surface Vehicle (ASV), MINION serves as:

- Propulsion and steering unit safeguarding against damage during bottom collisions, allowing mitigating additional hydrodynamic resistance: By incorporating a Pump-Jet thruster, which is enclosed and steerable, the

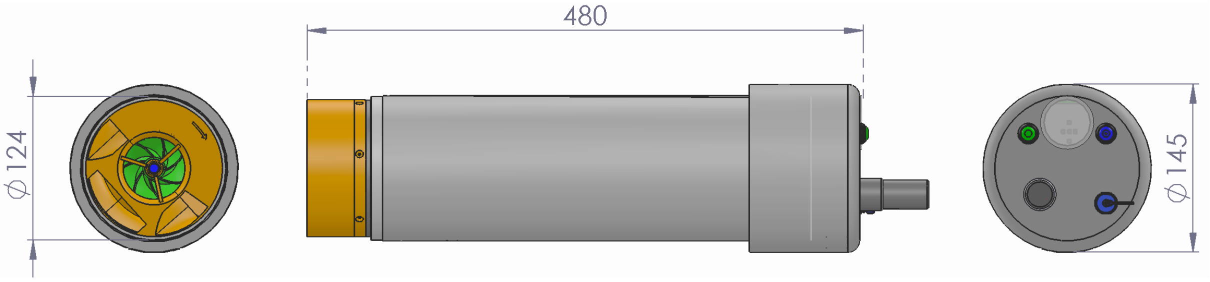


Figure 3: The MINION module overview size and encapsulation

MINION, minimizes the risk of entanglement or impact damage that traditional propellers might encounter in shallow environments.

- Onboard additional or principal computing element via Raspberry Pi 3b+: The MINION includes a Raspberry Pi 3b+ as its core computing unit. This versatile single-board computer can handle a range of processing tasks, from basic control functions of the Propulsion Unit to complex data analysis and decision-making algorithms. Its integration allows for onboard data processing, reducing the need for constant communication with external control systems and enhancing the vehicle's autonomous capabilities.
- Onboard additional or principal Navigation sensor-package element by integrating an IMU and a GNSS: The navigation capabilities of the MINION are bolstered by the inclusion of an Inertial Measurement Unit (IMU) that provides good attitude and orientation data by measuring acceleration and angular rates and a Global navigation satellite system (GNSS) module that delivers positioning information. Together, these sensors enable the MINION to navigate autonomously alone or installed on a vehicle, making it suitable for complex maritime environments requiring high degree of redundancy.
- Onboard additional or principal source of energy: The MINION is equipped with a 24V battery, serving as a power source for all its components. This battery not only powers the propulsion and control systems but can also ensure continuous operation to additional computing and sensor modules. By integrating the power supply within the module, the MINION enhances the vehicle's operational endurance and simplifies power management, eliminating the need for multiple external power sources and eliminating the cables.
- Wireless communication and removal of any cable from onboard: MINION incorporates wireless communication capabilities, enabling data transmission without the need for physical cables. This wireless connectivity simplifies the vehicle's operation, reducing potential points of failure and simplifying maintenance. By eliminating onboard cables, the MINION achieves a cleaner and more compact design, enhancing its maneuverability and reducing the risk of entanglement or damage during operation.

Conceived to create modular and independent systems, MINION is a watertight, detachable unit designed for easy transportation and adaptable deployment across diverse vehicles. The idea is that a MINION can be mounted on surface vehicles coupled with other independent modules as shown in fig. 4.

Additionally, the MINION architecture aims to incorporate automated FAIR (Findable, Accessible, Interoperable, Reusable) data compliance into marine robotics datasets Motta et al. (2023). This strategic initiative endeavors to establish standardized variable names, fostering domain interoperability and improving the findability, accessibility, and reusability of data collected by marine robotic systems.

5 Propulsion in MINION

Given the interest in ad-hoc solutions for wetlands monitoring, the authors defined a class of ASVs tailored to mission specifications. ASV design is based on guidelines from Odetti et al. (2018), inspired by Italian public and private organizations monitoring wetlands and shallow waters. Key design criteria for the Pump-Jet Module (PJM) include: (a) minimal draft for shallow waters; (b) survivability in grounding events; (c) high controllability; and (d) being lightweight and small. ASV propulsion systems often use commercial units, including free- or ducted propeller modules, water jet systems, and aerial systems (Figure 5).

In Odetti et al. (2019) the authors proposed a propulsion unit for an ASV design with an azimuth thruster, combining shallow water operation with satisfactory control. This thruster, named PJM, was developed for SWAMP ASV Odetti et al. (2020d,c).

Designed for shallow, confined waters and harsh environments, the PJM minimizes impact with waterway ground by using a flat bottom and specialized module. The PJM works in water depths as shallow as 50 mm

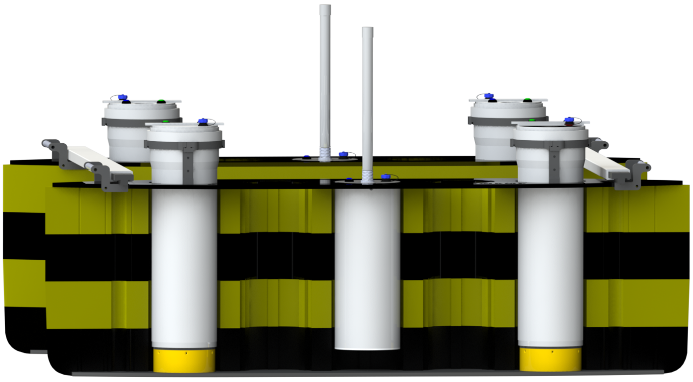


Figure 4: An example of four MINION mounted on SWAMP vehicle (Ferretti et al., 2023; Ferretti et al., 2023)

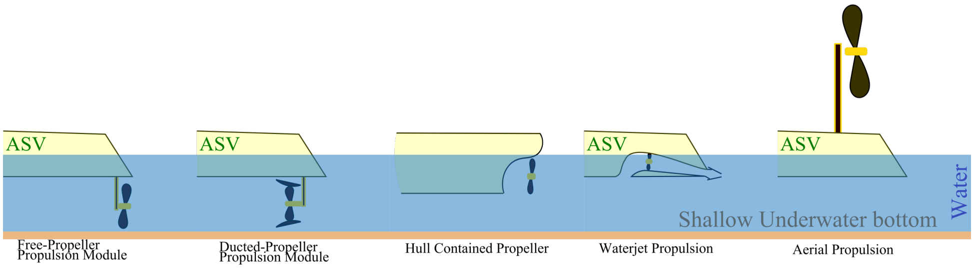


Figure 5: A schematic review of existing USV solutions

without risking damage, and its design minimizes damage from outcropping objects. ASVs need to access narrow areas and remain controllable in station keeping and path following, requiring an effective propulsion layout.

5.1 Pump-Jet System Description

As schematised in fig. 6, the Pump-Jet operates on the principle of vertical pump and is based on the application of the 3rd law of dynamics. Water is drawn into the thruster through a bottom-mounted intake on the vessel. Within the thruster, an impeller functions akin to a centrifugal pump: as it rotates, it accelerates the water, propelling it into a pump housing. The accelerated water is then expelled through a steerable nozzle positioned at the base of the thruster, generating a reaction force in the opposite direction and thus providing thrust to propel the vessel in the desired direction. This nozzle, integrated into the bottom plate, facilitates a flat-bottomed design and enables the installation of Pump-Jets in such hulls. By adjusting the nozzle's direction, precise control over thrust direction is achievable, facilitating vessel maneuvering. MINION boasts a 360-degree steerable nozzle, affording thrust capability in any direction around the vessel, thereby ensuring a good controllability.

The nozzle area at the bottom of the propulsion unit is about one third of the intake area, resulting in an outlet velocity four times higher than the intake velocity. This reduces the risk of sucking in unwanted objects in shallow waters.

The water is expelled at an angle of approximately 15 degrees from horizontal, converting almost all jet thrust into thrust. In shallow water, this minimizes disturbance to the bed, allowing for operations with limited impact as the expelled water rises toward the surface.

The high velocity of water exiting the nozzles enables the PJM to maneuver vessels at high speed, providing significant thrust due to the reliable intake performance of the mixed-flow pump.

The system is supported by a Housing made of PET and an Aluminum plate hosting two motors: the azimuth motor and the impeller motor. The azimuth motor provided with 59:1 gearbox and absolute encoder (2232X024BX4 with encoder AES-4096 and 22GPT 59:1 KS6 reduction by Faulhaber) shaft is connected to a driving spur gear made in PET that puts into rotation a driven spur gear (PET) connected to the Pump casing diffuser and nozzle providing thrust directionality. The controller (MCBL3002 P AES RS) is a Position Controller and it ensures that the motor maintains or reaches a specified position accurately with high precision. The homing

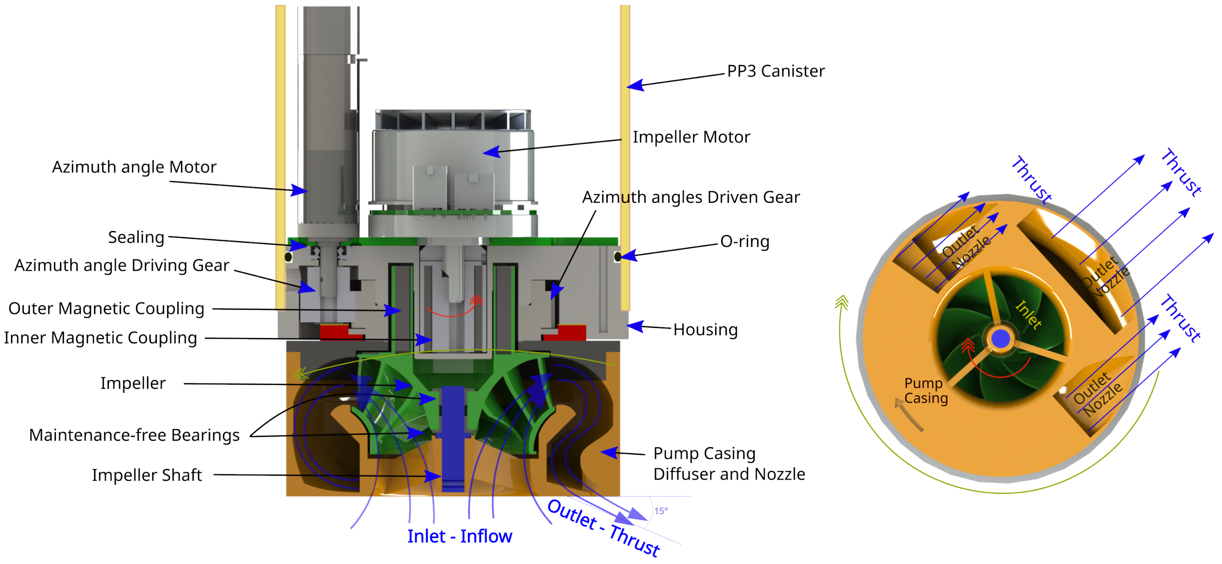


Figure 6: MINION’s Pump-Jet functioning scheme.

for the system is provided by a reed switch and a magnet present on the Pump Casing. The impeller is moved by a second motor (EC 60 flat Ø60 mm, brushless, 200 W, with Hall sensors - ventilated by Maxon Motors) coaxial with the impeller that provides thrust with a speed controller (ESCON Module 50/8). The Coupling is achieved by using a magnetic coupling that ad-hoc designed that internally is connected directly to the motor shaft and externally is structurally contained on the impeller’s structure. The impeller rotates on a Stainless steel shaft that is mounted on the Pump casing through two maintenance-free plain bearings (Igus). In terms of construction, the pump impeller, nozzle, and pump casing were all 3D printed in PA12. All the elements were made of lightweight inert plastics, so as not to compromise the environment where operates the ASV mounting the MINION.
The water-tightness of the mechanical system is ensured by a mechanical sealing on the azimuth side and by the presence of the magnetic coupling on the impeller side. A NBR o-ring sealing ensure water-tightness to the entire structure.
Inside the canister, the battery, the brushless motors, control electronics, Raspberry Pi and communication system are contained, making

5.2 Design Data

The design data for the Pump-Jet system included the project Thrust, project RPM, propulsor diameter’ the dimensioning of the Magnetic Coupling

5.2.1 Pump Design

The Pump-Jet based on the SWAMP ASV’s size and thrust needs, to calculate the pump the theory governing mixed-flow pumps was used to define the geometrical constraints underpinning the entire design.
The maximum diameter of the Pump-Jet Module (PJM) was defined based on the draught, payload, and dimensions of a small- to medium-sized ASV. Key geometric characteristics were identified to ensure the system could be scaled and matched to pump and vessel requirements. The casing height, and the inlet and outlet diameters of the impeller, were set proportionally to the main diameter. These dimensions, especially the outlet diameter, influenced the pump head and impeller RPM, crucial for motor selection. The water discharge angle was set at 15 degrees. The discharge nozzle was divided into three channels to achieve the required outlet area.

5.2.2 Propulsion Data

The design thrust of the MINION’s pump-jet was identified as $T = 15$ N. The value was obtained from tests conducted on SWAMP (Odetti et al., 2020c) and on the functioning of pump-jet at speed as described in Odetti et al. (2020a) where the results identified the full advance speed of the SWAMP hull in both shallow and deep water. Additionally, self-propelling tests characterized the Pump-Jet Module’s performance at various speeds and rotations. This enabled a thorough understanding of the module’s characteristics essential for effective control of the Autonomous Surface Vehicle. The thrust roughly originates from water flow multiplied by outlet water velocity. For this reason, all these parameters must be calculated in order to model the thrust unit. The vessel’s propulsion thrust is derived from the change in momentum when water enters and exits the jet thruster system (Altosole et al., 2012). Therefore, the thrust produced by the Pump-Jet (PJ) system is expressed as follows:

$$T = \rho_w A_n V_o (V_o - V_i) \quad [\mathrm{N}] \tag{1}$$

where A_n is the discharge area, V_o is the outlet flow speed, and V_i is the inlet flow speed. With respect to the output angle, the thrust is:

$$T_\alpha = \frac{T}{\cos \alpha_{out}} \quad [\mathrm{N}] \tag{2}$$

Here α_{out} is supposed not to be grater than $\frac{\pi}{6}$.
Since the value to be extracted is the outlet water velocity V_o, the water flow must also be calculated. To do so, we can use the equation:

$$T_\alpha = \frac{\rho_w A_n V_o^2}{\cos \alpha_{out}} \tag{3}$$

where V_i is, in the first approximation, negligible. This assumption holds since this value does not substantially influence the value of H_p. During the impeller design, a small inflow velocity was assumed possible due to vehicle speed (SPJ, 2019). As mentioned above, case-by-case tests were performed to evaluate PJM thrust at various ASV velocities.

The flow rate at the outlet is therefore:

$$m_f = \rho_w A_n V_o \quad [\mathrm{kg/s}] \tag{4}$$

$$Q_o = A_n V_o \quad [\mathrm{m^3/s}] \tag{5}$$

The data calculated above allowed us to define the pump head necessary for designing the impeller. From the Bernoulli equation:

$$P_i + \frac{1}{2}\rho_w V_i^2 + \rho_w g H_p = P_o + \frac{1}{2}\rho_w V_o^2 + \rho_w g \Delta h + \rho_w g h_{loss} \tag{6}$$

where H_p is the head associated with the pump, and P_o and P_i are the outlet and inlet static pressures, which are equal because the atmospheric pressure added to the water column is constant. Δh is the static difference in the head between inlet and outlet, which in this case was null, and h_{loss} is the term associated with the loss of head due to the flow through the system and the pump. The h_{loss} value was added as a η_{loss} coefficient to the value of the pump head. This allowed to calculate the total head of the pump:

$$H_p = \left(\frac{V_o^2}{2g} - \frac{V_i^2}{2g} \right) / \eta_{loss} \tag{7}$$

In addition, the power associated:

$$P_{pump} = \rho_w g Q_o H_p \tag{8}$$

Using this value, it is possible to identify the pump type by calculating the pump specific speed:

$$N_s = \frac{n\sqrt{Q_o}}{H_p^{0.75}} \tag{9}$$

5.2.3 *Calculation of Parameters for the Pump-Jet*

Based on the above equations the design of the Pump-Jet propulsion system required the following methodology for calculating key parameters necessary for the Pump-Jet design. In order to determine the appropriate pump head (H_p) required to achieve the desired thrust, the Bolzano Theorem is employed. By iteratively varying the pump head within a specified range, an optimal value of H_{pj} is sought. This process involves computing the outlet velocity (V_{oj}) using the derived formula from the Bernoulli equation, where H_{pj} is incrementally adjusted.

$$V_{oj} = \sqrt{2gH_{pj} - \frac{2(p_o - p_i)}{\rho_w} + V_i^2} \tag{10}$$

The difference between the calculated thrust and the desired thrust is then evaluated to iteratively approach the optimal H_{pj} value. Finally, the index corresponding to the minimum difference is identified to obtain the most suitable $H_{pj} = H_{p_0}$ value for the given thrust requirement. To obtain the actual pump head (H_p), a correction is applied to the theoretical pump head (H_{p_0}) to account for pump efficiency (η_{pump}):

$$H_p = \frac{H_{p_0}}{\eta_{pump}} \tag{11}$$

With the corrected pump head, the outlet velocity (V_o):

$$V_o = \sqrt{2gH_p - \frac{(p_o - p_i)}{\rho_w} + V_i^2} \tag{12}$$

and flow rates (Q_o) are computed.:

$$Q_o = A_n \cdot V_o \tag{13}$$

The inlet (V_{ii}) and outlet (V_{io}) velocities of the impeller are calculated based on the determined flow rates:

$$V_{ii} = \frac{Q_o}{A_i} \quad ; \quad V_{io} = \frac{Q_o}{A_{io}} \tag{14}$$

With this the Specific Pump Parameters are then computed. The pump specific speed (N_s) is derived from the corrected pump head and flow rates:

$$N_s = \frac{n_{prog} \cdot \sqrt{Q_o}}{H_p^{0.75}} \tag{15}$$

Additionally, an imperial unit equivalent of pump specific speed (N_{sgpm}) is computed for practical comparison and analysis. By following these calculations, it was possible to design the Pump-Jet propulsion system by defining parameters as diameter ratios, coefficients, and geometrical factors

From Stepanoff (Stepanoff, 1957) coefficients, derived from empirical data or equations to account for specific performance characteristics of the impeller design, are introduced. These coefficients serve as crucial factors in optimizing the impeller's performance. Inlet, Outlet, and Intermediate geometries are then calculated and defined, to calculate the various sections of the impeller. After this the velocity triangles, detailing velocity components and angles at different impeller stages, are computed. Blade height is determined from Stepanoff influencing fluid flow and pressure distribution. Angles at the inlet, outlet, and intermediate stages are then calculated to design the blades and the pump geometric in automatic.

After this phase a MATLAB Code was implemented to design the Pump-Jet fluid elements. The code includes constants and parameters for fluid properties, pump geometry, and efficiency, and it uses these inputs to calculate thrust, flow rates, and the performance characteristics of the pump-jet.

In fig. 7 it is reported the outcome of the code. The maximum torque provided by the coupling occurs when the magnets are shifted by 30 degrees. This is because the maximum attraction on one facing magnet coincides with the maximum repulsion from the adjacent magnet, which has reversed polarization.

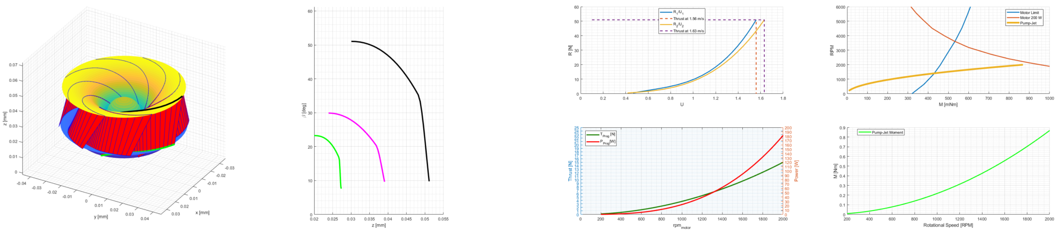


Figure 7: An example of the output of the MATLAB code used to calculate and design the pump-jet of the MINION

5.2.4 *Permanent-Magnet Coaxial Synchronous Coupling*

In this section, it is presented the analysis and optimization of the torque of the permanent-magnet coaxial synchronous coupling used to couple the Impeller motor to the Impeller itself. The advantage of magnetic coupling is that it eliminates the need for traditional shaft seals, reducing the risk of fluid leakage and environmental contamination. Furthermore by eliminating the need for dynamic seals, maintenance requirements are minimized, resulting in lower operating costs and increased uptime.

The optimization process focuses on the magnetic properties and geometrical parameters of the magnets involved and it is based on Charpentier and Lemarquand (1999) and Eliès and Lemarquand (1998). The process utilized MATLAB for the calculation and visualization of the force and torque interactions between the magnets, ensuring the optimal design parameters were identified.

In fig. 8 it is reported the outcome of the code. The magnets are faced with opposite poles facing in order to create an attractive force. Each magnet has the polarisation inverted in respect to the nearest magnet. When two magnets face each other, the exerted force becomes radial, resulting in a tangential component of zero. This configuration is stable. As the internal magnet rotates, the tangential force on the external magnet initially increases rapidly, peaks at a maximum, then gradually decreases to a relative minimum before returning to zero (Eliès and Lemarquand, 1998). Deriving the analytical formula provides the rotation angle values corresponding to maximum or minimum points of the tangential force component was the outcome of this calculation. Since the number of facing magnets chosen was 6 (3 poles) in the code also the calculation of the repulsive force created when the internal magnets starts entering the repulsive field of the following external magnet had to be calculated. In the MINION, Neodymium magnets where used with a magnetic flux density of 1.23 Tesla.

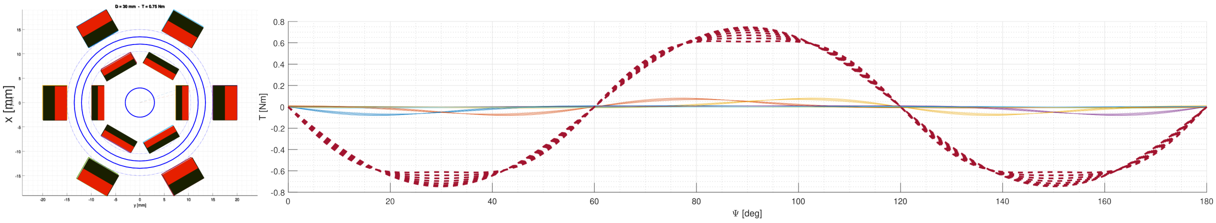


Figure 8: On the left the geometry of the Magnetic Coupling with Magnets faced with reversed poles. On the right the calculation output of the MATLAB code used to calculate the Magnetic Coupling of the pump-jet

5.3 Control System Hardware architecture

The MINION control system hardware architecture is based on the Raspberry Pi 3.0 model B SBC (Single Board Computer) running the Raspbian OS (Operating System). Raspberry Pi boards are inexpensive but very powerful computers based on ARM processors. The Raspbian OS (see https://www.raspbian.org/ for details) is a derived version for ARM processors of the Debian OS (a GNU/Linux-based OS). One of the main characteristics of the Raspberry Pi is the possibility to easily interact with a number of different hardware devices thanks to the presence of 4 USB 2.0 and of a 40-pin GPIO (General Purpose Input Output) header providing a number of interfaces options: digital I/O, PWM (Pulse Width Modulation), I2C (Inter-Integrated Circuit), SPI (Serial Perihperal Interface), serial. Additional digital, analog, serial, etc. I/O channels can be easily added to the SBC thanks to the expandability guaranteed by the presence of the USB, I2C, SPI and serial interfaces.

In particular, on the one hand, the SPI interface was used to communicate with additional A/D and D/A integrated circuits (i.e. MCP-4922 and MCP-3208) necessary for interact with sensors and actuators requiring analog signals.

Power on/off, enable/disable and faults signals are managed by means of the digital I/O channels (GPIOs) directly provided by the Raspberry Pi.

On the other hand, the I2C interface was used to communicate with a supplementary low-cost, extremely accurate RTC (Real Time Clock) based on the DS3231 integrated circuit. The time of the RTC is used for the synchronisation of the telemetry created by the system. The presence of a USB storage system onboard allows for the saving of this telemetry onboard the MINION itself.

On the Raspberry Pi is running a low level control system application called *minion* written in C++ that manages the various sensors and actuators communicating with the SBC by means of the above mentioned interfaces.

The schematic representation of the MINION's control system hardware architecture is reported in fig. 9.

As far as the sensors are concerned the following devices are managed by the control system:

- Adafruit BNO055 absolute orientation sensor: an IMU (Inertial Measurement Unit) providing absolute orientation (yaw, pitch and roll), angular velocities and linear accelerations - digital connection of type RS-TTL;
- U-blox ZED-F9P absolute position sensor: providing GNSS (Global Navigation Satellite System) positions - digital connection of type USB (virtual RS-232);
- temperature sensor providing internal temperature measurements - analog connection;
- voltage sensor providing battery voltage measurement - analog connection.

As far as the actuators are concerned the following devices are managed by the control system:

- Thruster motor: providing thrust - both digital and analog connections;
- Azimuthal motor: providing azimuthal control of the thrust - both digital and analog connections.

For further expansion of the control system plentiful analog and digital I/O channels are available.

Moreover the Raspberry Pi also provide a Wi-Fi interface that permits to communicate with the analogous hardware control systems located inside the other MINION modules.

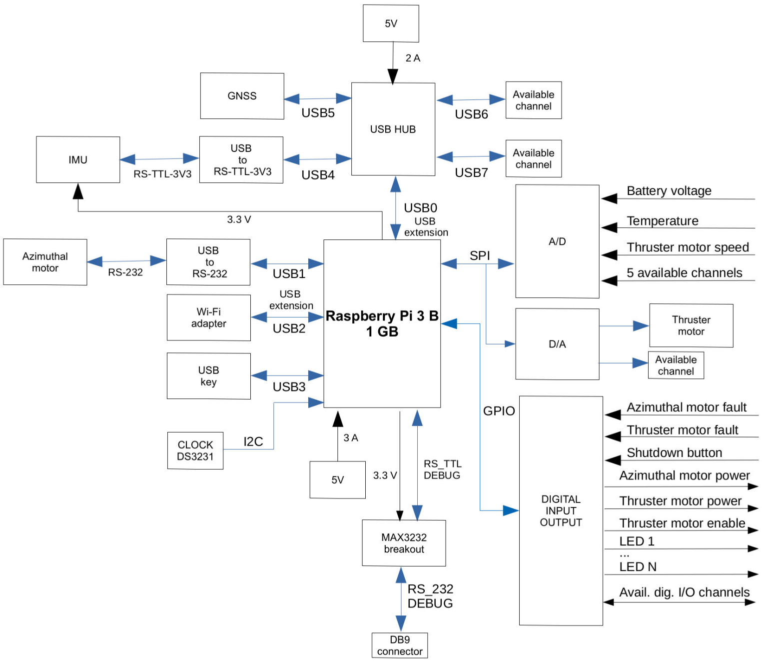


Figure 9: MINION's Control System Hardware Architecture

5.4 *Powering*

A Lithium-ion battery comprises seven cells in series and five sets of cells in parallel. Each cell has a nominal voltage of 3.7V and a capacity of 2600mAh. The total battery voltage is 25.9V, with a capacity of 13Ah. It offers a power capacity of 336.7Wh and 9.62Wh per cell. Li-ion batteries are prized for their energy density, lightweight and rechargeable properties, finding use in diverse applications from electronics to electric vehicles. The charging system provides 10 Ah thus giving the possibility of recharging the MINION in almost 1 h.

The MINION system is provided with possibility of battery bypass, enabling the integration of external power sources to supply energy to the system. This feature not only ensures continuous operation but also promotes the versatile utilization of onboard energy resources, enhancing the system's adaptability across various applications.

A system of solid state DC-DC converters are used to: stabilise the 24 V powering required by the motors, converting energy to various users, especially Raspberry Pi that requires 5 V for its operations.

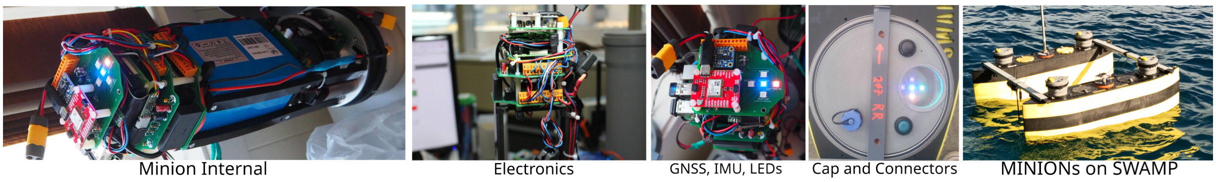
6 Conclusions and further research

MINION (shown in fig. 10) serves as a propulsion and steering unit for ASVs. Only one MINION can be used as a single vehicle, being provided with all the features required for a marine robot, or to create a distributed robot. Its Pump-Jet thruster design reduces the risk of entanglement or impact damage in shallow water environments. From its inception, it was designed not just as a mere propulsion unit but as a comprehensive solution, integrating propulsion, navigation, computation, and sensing capabilities into a compact and adaptable package. Its integration with GNSS and IMU ensures precise navigation, allowing for accurate data collection and autonomous decision-making, essential for tasks ranging from maritime surveillance to underwater exploration. Being equipped with a Raspberry Pi 3b+ for onboard computing, this computing power enables real-time data processing, facilitating autonomous navigation and enhancing computational space onboard the vehicle. Coupled with wireless communication capabilities, MINION enables data transmission, enabling effective coordination between vehicles and human operators.

One of MINION's defining features is its modular design, which allows for easy integration with additional sensor modules. This modularity opens up a plethora of applications, from environmental monitoring to oceanographic research. Beyond its practical applications, MINION served in its early developments as an educational platform, providing students with hands-on experience in robotics, marine engineering, and autonomous systems.

6.1 *MINION in Dynamic Positioning*

The MINION concept, through its integration of propulsion, power, intelligence, sensors, and communication, offers a transformative approach to Dynamic Positioning systems. Its modularity, redundancy, and comprehensive functionality was intended to align with the requirements of various DP classes, thereby enhancing the reliability,



Minion Internal Electronics GNSS, IMU, LEDs Cap and Connectors MINIONs on SWAMP

Figure 10: MINION Pictures. From Left: MINION internal construction (Electronics, Raspberry, Power Management, Battery, Motors, Mechanics); MINION electronics; Sensors and LED lights; Cap with connector for charging and buttons; MINIONs mounted on SWAMP

safety, and operational flexibility of maritime and offshore operations.
The initial idea of MINION concept was to meet and enhance the requirements of Dynamic Positioning (DP) systems.

6.1.1 Dynamic Positioning System Requirements

Dynamic Positioning (DP) (Sørensen, 2011; Alfheim et al., 2018) systems are critical in maritime and offshore operations, ensuring vessels and platforms maintain their position in challenging environments. Redundancy is essential to the reliability and safety of DP systems. The International Maritime Organization (IMO) classifies DP systems into four grades (DP Class 1 to DP Class 4) based on their redundancy and capabilities (DNV, 2016; MSC, 1994).

6.1.2 Benefits of the MINION Concept for DP Systems

The MINION concept offers numerous advantages for DP systems, enhancing their redundancy, capability, and flexibility in accordance to failure modes described in the rules (DNV, 2012). In terms of **redundancy**, the MINION units provide distributed thrusters across the vessel. This modularity ensures continuous position control even if some units fail. Each MINION unit contains its own power source, reducing dependence on a central power system and ensuring continuous operation. Additionally, the integrated sensors (GNSS, IMU) in each unit enhance the accuracy and reliability of position and heading data. The embedded computing capabilities in each unit allow for autonomous or collective control, ensuring functionality despite individual processor failures. The built-in communication systems in each MINION unit ensure continuous connectivity, providing multiple communication paths for reliability. The **capability and flexibility** of the MINION units are also significant. The steerable nozzles allow for 360° thrust control, improving maneuverability and position maintenance. The compact, watertight design of the MINION units facilitates easy installation, removal, and reconfiguration. Vessels can be equipped with varying numbers of MINION units to meet specific DP class requirements, from basic redundancy (DP Class 1) to high redundancy (DP Class 4). The robust design of the MINION units provides protection during bottom collisions, maintaining positioning capability even during impacts. Moreover, the MINION architecture adheres to **FAIR data principles** by supporting standardized variable naming conventions, ensuring that data generated is Findable, Accessible, Interoperable, and Reusable. In critical failures, the MINION units can switch to manual control or activate emergency disconnect systems, enhancing overall safety.

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