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RESEARCH ARTICLE

Hybrid Control Architecture of an Unmanned Surface Vehicle Used for Water Quality Monitoring

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ABSTRACT The study of water quality in reservoirs, lakes, and coasts is an activity that mainly uses human-crewed marine vehicles to obtain site parameters such as temperature, conductivity, salinity, pH, and others. This task is facilitated by unmanned vehicles, which improve data quality in hazardous areas and minimize human exposure. This work presents a novel methodology based on systems engineering concepts and hybrid control architecture for a catamaran-class unmanned surface vehicle (USV) named *EDSON-J*, for remote water quality monitoring activities with payload instrumentation. Critical aspects of the project development are considered, such as requirements, risk management, design flexibility, logical decomposition, functional classification, verification, integration and validation, and technological plan. The applied methodology proposes the main components for the vehicle, a main computer running robotic operating system (ROS) with deliberative control architecture for high-level tasks and a secondary computer running finite state machine (FSM) with hierarchical control architecture for low-level tasks, executing control and navigation algorithms. The results are given through missions of water quality monitoring, attaching a multiparameter payload sonde. Manual and automatic mode controls are suitable for circular and zig-zag maneuvers and show better performance for the proposed platform, guaranteeing the specifications and requirements of the vehicle design and validating the proposed hybrid control architecture.

INDEX TERMS Unmanned surface vehicle, hybrid control architecture, systems engineering, remote monitoring, water quality.

I. INTRODUCTION

Water pollution is a global problem due to unsustainable industrial activities and the lack of public policies in some countries. Population growth, industrial and mining activities increasingly intense, demand large amounts of fresh water in reservoirs and lagoons. Therefore, monitoring and studying water quality are essential to guarantee the health of inhabitants [1]. More frequent monitoring can prevent environmental damage. For example, in Peru, a study on water quality measurements has evidenced the presence on sulfides in the Auri and Rimac rivers caused by small-scale mining [2]. For these reasons, water quality monitoring methods should be improved and made more intensive following government policies, such as water resource quality recovery strategies [2].

A solution for measuring water quality is to use a wireless sensor network (WSN) in which sensors are placed along the shore and transmit data in real-time, as was done in a pilot project in England [3]. However, unmanned vehicles is

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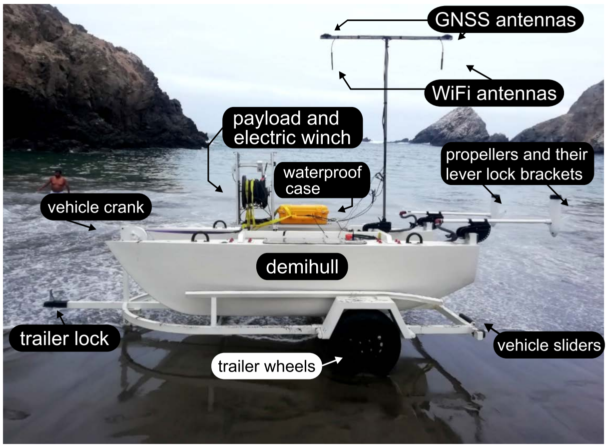

FIGURE 1. ***EDSON-J*** **USV on a trailer towed by a pickup truck close to the coastal waters.**

a portable and affordable solution over time, dispensing with the need for repetitive sensors. The use of unmanned vehicles for an extensive study on water quality monitoring can be found in [4]. Unmanned autonomous vehicles need intelligent planning algorithms [5], collision detection [6], and guidance algorithms [7], [8], in order to successfully perform their missions.

Unmanned surface vehicles (USVs) are a type of autonomous vehicle aimed to measuring and monitoring water quality. Among its applications, it can detect heavy metals and dispersed oil up to 50 meters as a remotely operated submersible vehicle (ROV) [9]. In addition, a USV can operate in cooperative missions for contaminant source detection in a dynamic aquatic environment [10]. USVs are also used to solve environmental problems, such as water spills; novel techniques generate optimal trajectories for USVs in liquid contaminant suction missions [11]; low-cost USV initiatives are thus being developed for less than \$300, whereby ship hydrodynamics or certified payload instrumentation are neglected, with the drawback of being an unfeasible solution for governmental and industrial official reporting. However, they are used to develop water cleanup techniques [12] and provide open source solutions [13].

Another alternative for water quality monitoring is to load all instrumentation or appropriate probes on an autonomous underwater vehicle (AUV), supported by a USV for accurate location data [14]. Recent articles report novel navigation control approaches for autonomous USV networks, with potential applications to more intelligent water quality monitoring [15].

In [16], the design of a hybrid control architecture for autonomous mobile robots is proposed in which the virtues of several architectural approaches, such as reactive, deliberative, distributed, and centralized, are exploited. Many works on AUVs are influenced by the hybrid control architecture, which combines these approaches with systems engineering concepts dedicated to the methodology and to the design of an unmanned vehicle [17]. Some artificial intelligence approaches can also be considered at the reactive layer, and other intelligent control architectures enable cooperative missions for multiple maritime vehicles [18]. Hybrid architectures focus more on accomplishing vehicle missions than those that address a single paradigm [19]. Another recent approach that explores hybrid architecture in a new class trimaran surface vehicle can be found in [20].

The *Universidad Nacional de San Agustín de Arequipa* has recently developed a USV called *EDSON-J* (Fig. 1), dedicated to environmental monitoring of water resources in areas vulnerable to contamination. The novel contribution of this paper is the new methodology that establishes a hybrid control architecture based on systems engineering concepts, initially defining requirements, risk management, design flexibility, logical decomposition, functional classification, verification-validation-integration, and the technological plan of the resulting prototype.

This paper is organized as follows: Section I presents an introduction focusing on the motivation for the paper, related work, and contribution. Section II presents the development and the concepts of systems engineering applied to the USV. Section III presents the hybrid control architecture which is the proposed methodology. Section IV presents the results performed in a real mission of water quality monitoring, using manual and automatic controls. Finally, section V presents the conclusions together with the future direction of this research.

II. DEVELOPMENT

EDSON-J is an unmanned surface vehicle designed to perform water monitoring missions of large reservoirs, lakes, and coastal waters. The USV is conceptualized to support large and heavy payloads such as multiparameter sonde, multibeam sonar, doppler velocity log (DVL), and samplers. The USV is conceptualized to support large and heavy payloads. The overall system must provide flexibility to integrate them into the system. Therefore, guidelines based on system engineering concepts are used to project an optimal development in vehicle engineering [21].

A. REQUIREMENTS

In this initial stage, the minimum specifications to be met by the USV are defined. As the overall objective is to measure water quality parameters in real-time during navigation, the requirements of the control architecture are defined in terms of physical capacity, environmental conditions, simplicity, and scalability of its components. A list of requirements to be addressed is shown:

- Mission range of at least 18 km.
- Cruise speed of 1 m/s.
- Capability of sampling water at a maximum depth of 100 m.
- Length <3.2 m, breadth <1.6 m, and maximum weight <250 kg.
- Maximum operative conditions (wind speed 10 - 15 km/h).

- Payload mass of at least 70 kg.
- Ease to tow by a 4 × 4 pickup truck to be transported from the campus to the mission location (500 km maximum).
- Ease to assembly and disassembly, 30 minutes by operation.
- Low draft of the vehicle hull to protect the propellers from possible impact with the floor.

B. RISK MANAGEMENT

An analytical basis of potential risks is established to be considered in case of an unexpected event and proactively available solution strategies, both in laboratory and at remote mission sites. A list summarizing the significant risk sources in vehicle development, operation, and maintenance is presented.

- Electric shock due to malfunction of power circuits.
- Damage in electronic boards due to poor waterproof protection of the cases and connectors.
- Malfunction, when the privileges and permissions are neglected for access to the main computer.
- Neglected weather conditions when it operates in lakes and oceans.
- Loss of remote control due to failure in the communication system.
- Accidents and collisions when the remote control is lost.

For electrical hazards, insulators and sealing cords were used in order to avoid short-circuits due to accidental water leakage into catamaran hulls. The electrical connectors from the battery to the external propellers are certified following the standard IEEE 45.5-2014 and guidelines to prevent electrical hazards. The actions taken have ensured that there have been no incidents in the last ten months according to experimental reports. Good practices such as using certified connectors with IP68 protection, backups, constant revision of the system's hardware and software, prevention in the operating environment and limitations in the wireless operating range have guaranteed that the USV operates correctly.

C. DESIGN FLEXIBILITY

Design flexibility in a complex system such as a USV is a feature that highlights the versatility of the vehicle for different applications. The hull shape of the catamaran favors this feature due to the space and mass available for the payload. According to the hybrid architecture, in the deliberative layer, the robot operating system (ROS) allows the inclusion of new subsystems depending on the required applications defined by the user. For example, in a future mission considering computer vision, stereoscopic cameras can be easily included through the main computer ports, and the respective nodes will be included in ROS. As for the control architecture, the use of converters from industrial protocols to universal serial bus (USB) is established as a fundamental part of the design flexibility due to the multiple varieties of converters available on the market for different types of industrial protocols, such as RS-232 or RS-485. As test instrumentation, we use a multiparameter probe with RS-485 industrial protocol connected to a USB converter and directly to the main onboard computer.

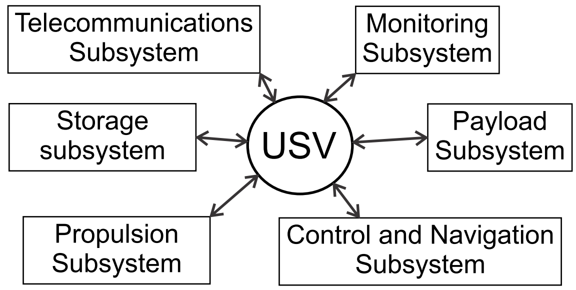

FIGURE 2. USV ***EDSON-J subsystems.***

Finally, the subsystems are defined, each of which has a specific purpose, and operation as a whole converges to the operation of the complete vehicle. Fig. 2 depicts these assemblies that can be easily added, modified, or removed. The main tasks of the USV are divided into the following subsystems:

- Telecommunications subsystem: Composed of long-range Wi-Fi antennas, it provides wireless communication between the operator and the USV during the mission.
- Monitoring subsystem: Composed of the graphical user interfaces (GUI), it displays the vehicle status and sampling parameters.
- Payload subsystem: It is the subsystem dedicated to obtaining parameters with the selected instrumentation; for this work, a multiparametric water quality probe is used.
- Control and navigation subsystem: Composed of the secondary computer and the inertial navigation system (INS), they control the dynamics of the vehicle in the water according to the instruction received. It will generate the necessary instructions to move the USV.
- Propulsion subsystem: Composed of thrusters, driver motors, and high-power batteries, the power subsystem interprets the signals from the control and navigation subsystem.
- Storage subsystem: Its objective is to store all the information of the start and stop of the vehicle; it stores every hour in databases such as instructions, vehicle status, and payload parameters.

D. LOGICAL DECOMPOSITION

It is the functional analysis by defining an architecture in the system for each assembly, as it is organized to specify the requirements to be met by each vehicle subsystem. In the USV, a control architecture is proposed that combines two different approaches, deliberative and hierarchical, due to the advantages each offers for different applications and that, for the future, favors the flexibility of missions to be assigned.

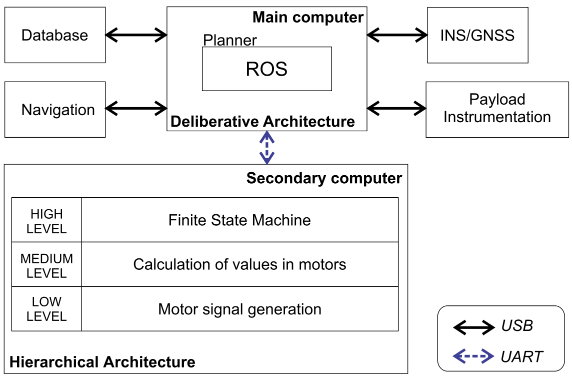

FIGURE 3. General classification of general functions within the hybrid control architecture.

The main computer runs a glider, characteristic of the deliberative architecture, which governs and arbitrates high-level tasks, including payload data management, navigation mode, database, telecommunications, and the ROS. It is managed remotely through Secure Shell (SSH) protocol from the base station, using the local area network.

The hierarchical architecture in the secondary computer establishes levels of operation in which a state machine is located as the top level for calculating values in the propellers. It communicates with the intermediate level in charge of generating values in each propeller and, finally, at the lowest level, the power signal generation that activates the actuators. In ROS, the secondary computer is a hardware (USB to TTL Serial) that sends and receives serial messages at a rate of 115200 baud; the secondary computer receives the information as a high priority universal asynchronous receiver-transmitter (UART) interrupt and updates the state machine. The hierarchical architecture distributes in series a set of tasks whose purpose is the navigation of the vehicle.

E. FUNCTIONAL CLASSIFICATION

It is the organized classification of general system functions. The highest priority tasks are executed in the main computer under deliberative architecture. Each of them is connected through USB protocol, for example, inertial navigation system and multiparameter sonde as payload through RS-485 to USB converter. Fig 3 shows the functional classification of the USV. The communication between the host and secondary computers is made with a UART to USB converter. Then, in the hierarchical architecture, the communication of the microcontroller and controllers is made only with UART.

F. VERIFICATION, INTEGRATION AND VALIDATION

This subsection details the verification of parts, integration of subsystems, and validation of USV performance. *EDSON-J* is assembled in laboratory, with hardware debugging tools, software, and advice from experienced programmers. The software verification is evaluated under the criteria of standard programming guidelines, as is the case of the secondary computer with MISRA C. On the hardware, the verification is determined individually on the component assemblies, mainly the IEC 60529 standard that guarantees electronic protection against dust and water. In the integration stage, all the parts are joined to conform to the vehicle system. External components, such as propellers, payload, communication antennas, and global navigation satellite system (GNSS) receiving antennas, are exposed to the weather; their connections to the main computer are thus made with certified waterproof connectors. Internally, the integration stage runs smoothly due to the deliberative architecture, which is implemented at a high level. Connections are as easy as plugging USB connectors into a computer. After integration, the essential stage of this subsection begins. Validation allows the development team to ensure that the vehicle is fully functional and that the mission risk should be minimized in a hectic environment such as navigation. For this, multiple tests are developed on land and in low disturbance ponds, allowing us to know the initial parameters of:

- Payload subsystem.
- Manual and automatic navigation functions.
- Maximum remote connection range and latency.
- Line-of-sight and obstructed intercommunication.
- Battery energy efficiency.
- Propulsion subsystem.
- Accuracy of the navigation subsystem.
- In-situ database storage of all sensors and actuators.
- Mechanical resistance of the catamaran against vibrations.
- Internal and external resistance of connectors against vibrations.

G. TECHNOLOGICAL PLAN

A plan is established to recognize and define technical efforts in the parts of the system to meet the requirements. Initially, a computer that meets the requirements of flexibility, native compatibility with Linux and Python, computational power, and energy efficiency was chosen as the main computer. The Jetson TX2 computer meets this requirement thanks to its NVIDIA Pascal GPU, with high bandwidth for processing up to 50 GB/s, good energy efficiency, and scalability to implement more advanced functions for the USV.

About the secondary computer, in works as in [17], the ARM family of microcontrollers is an excellent choice in terms of open source tools with free access, energy efficiency, computational power, and small footprint. A high-performance 32-bit ARM RISK M4 microcontroller is chosen. The device selected was the TM4C123G microcontroller, with a wide variety of applications in embedded systems over time and an active community in the manufacturer official forums. The secondary computer is in charge of the subsystem that controls the thrusters, receives orders from the main computer, and is in charge of interpreting them on the thrusters. Minn Kota electric propellers of 55 Lbs of thrust force were chosen because of their power at such low

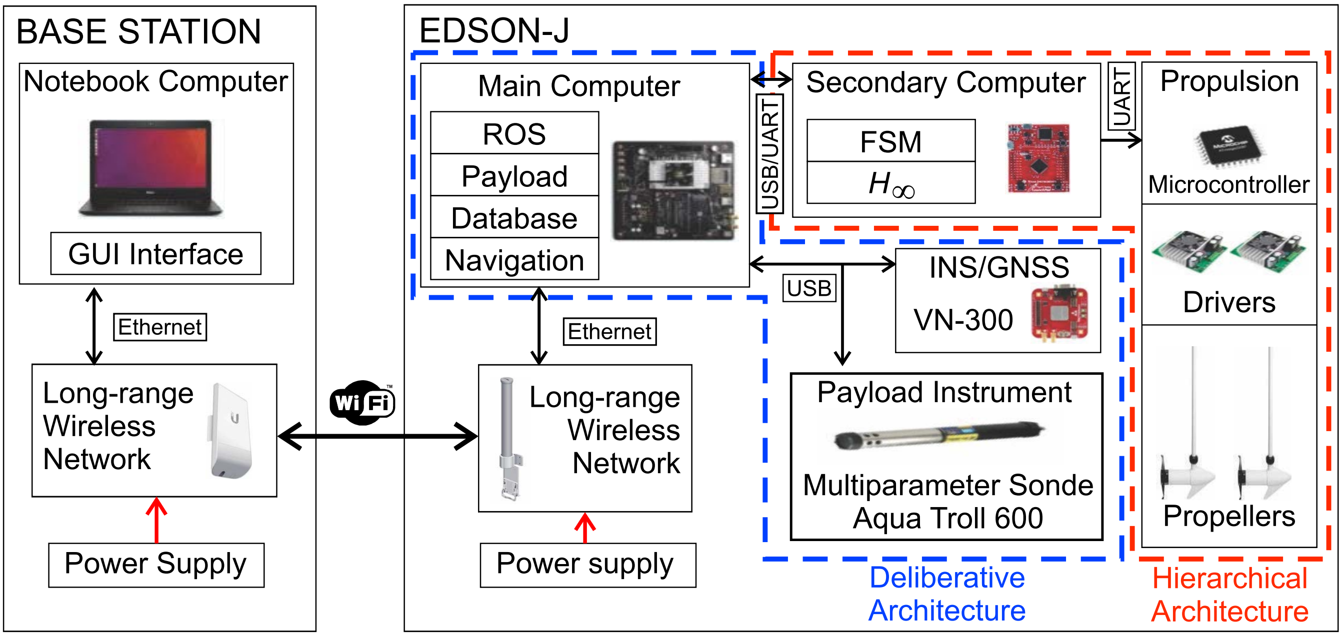

FIGURE 4. USV control architecture *EDSON-J* for remote monitoring from a base station to the vehicle during navigation using a reliable Wi-Fi wireless connection.

weight and size. These are controlled by PWM signals from a high-power driver and an ATmega328P microcontroller.

Both computers remain inside an electronic case in the USV, completely protected from the weather and fixed on a modular grid that supports and manages them electronically.

A single device handles the navigation subsystem, the VN-300, consisting of a dual global navigation satellite system assisted by an inertial navigation system (INS/GNSS), has excellent navigation accuracy, and facilitates data processing tasks since it internally calculates, filters, and delivers the data in national marine electronics association (NMEA) format character strings via USB and UART port. According to studies that have used VN-300 [22], this device has a positioning availability of 99% and an accuracy in the horizontal plane of 1 m, making it suitable for mission tasks.

Thanks to industrial protocol converters, the payload is configured as a USB device. For this article, an Aqua TROLL 600 multiparametric sonde is used to connect to the main computer by an RS-485 to USB protocol converter. On the main computer, a script is developed that runs under the planner management and reads records of the information acquired by sensors in the sonde, stored in the database, and transmitted in real-time.

Interfaces (GUI) were developed, and the first GUI displays water quality monitoring on an open-access platform [23]. The second GUI monitors the navigation of the vehicle on the water and provides information about the USV dynamics, such as Euler angles, velocity, position, altitude, motor value, and current command as a function of time.

Tab. 1 presents the details and cost of the main components of the *EDSON-J* unmanned surface vehicle. It did not include the cost of the multiparameter sonde, the logistical

TABLE 1. List of main components and costs of the USV.

Component	Model/Detail	Quant.	Cost ($)
USV hull	Catamaran	1	10000
INS/GNSS	VN-300	1	5000
Main computer	JetsonTX2	1	1500
Secondary computer	TM4C123GH6PM	1	40
Waterproof case	1500 Protector Case	1	300
Microcontroller	ATmega328P	1	10
DC regulator	100 W Buck converter	2	20
USB to TTL converter	FTDI manufacturer	2	10
RS-485 to TTL converter	FTDI manufacturer	1	10
USB hub	Generic	1	10
Frame	Aluminum	1	15
Propeller	MinnKota 12 V 55 Lbs	2	300
Driver motors	DC serial controller	2	100
Li-Po batteries	12V 5000 mAh	4	50
Lead batteries	12 V 100 Ah	2	200
High-current connectors	Surlock Amphenol	4	50
Data connectors	4000 Series Bulgin	5	20
Long range wireless	Ubiquiti	1	250
Notebook Computer	Dell Core i5	1	1000

cost of transportation for validation in real scenarios, or additional supplies. The research grant agency, mentioned in the acknowledges section, covers all the development costs, including disseminating the results in former conferences and papers.

III. HYBRID CONTROL ARCHITECTURE

The distribution of the elements that make up the complete system architecture is shown in Fig. 4, and two main blocks are observed. The first one is where the operator has access to the USV from the base station through a GUI, where he/she can monitor the water quality parameters and manipulate the navigation in real-time, using a long-range wireless link in

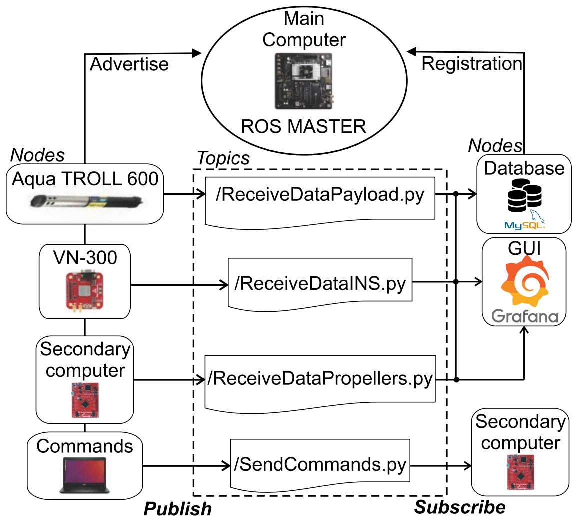

FIGURE 5. Communication diagram in ROS. Distribution in the information interchange between publishing nodes and subscribers through topics.

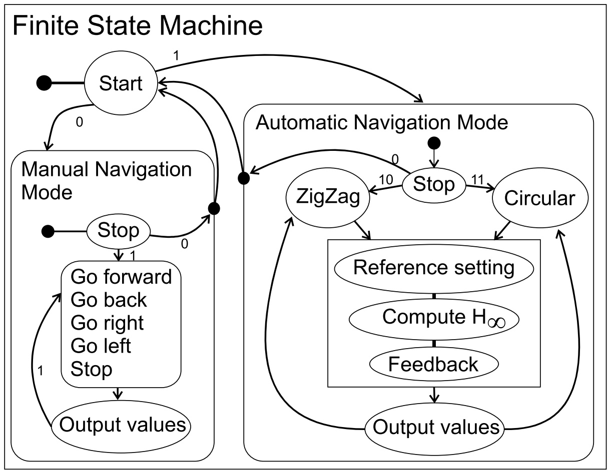

FIGURE 6. The finite state machine in the secondary computer is in charge of generating values for the thrust in the USV thrusters.

FIGURE 7. EDSON-J on a regular mission for water quality monitoring in a huge reservoir in Majes - Arequipa (latitude: −16,388 longitude: −72,195). This reservoir contains about 50 000 m^3 of fresh water from the Andes for rural irrigation in the city.

the 5 GHz free band spectrum. The *EDSON-J* right block shows the deliberative and hierarchical architectures.

The deliberative architecture contains the main computer, high-level tasks, INS/GNSS, and payload instrument, allowing any device to be easily integrated into the system using the USB protocol due to the planner running on the main computer. The planner manages the high-level tasks and bases its decisions on the operator and pre-set indications.

Devices connected to the host computer or high-level tasks are nodes (Fig. 5). Nodes that provide data are referred to as publisher nodes and nodes that receive data as subscriber nodes; "topics" are data published by one node that multiple subscriber nodes can receive. Subscriber nodes receive data from publisher nodes only if they are available. This is organized by the planner, in other words, ROS Master.

The publishing nodes of the *EDSON-J* are the Aqua TROLL 600 multiparameter sonde, the INS/GNSS VN-300, the secondary computer, and the commands from the operator at the base station. The subscriber nodes are the database, the GUI, and the secondary computer. The system topics are responsible for receiving payload data, the INS/GNSS data, thruster actuation information, and commands from the operator on the ground.

The hierarchical architecture contains the navigation subsystem devices, such as the secondary computer, ATmega328P microcontroller, DC motor drivers, and propellers. The advantage of the hierarchical control architecture is the execution of tasks in stages, i.e., a distribution of functions in series along with the layers, which distribute the workload. This facilitates organized operation from the highest layer (state machine) to the lowest (drives).

The uppermost layer is the state machine represented in Fig. 6, a tool that is the core of the navigation subsystem. It receives commands from the main computer depending on the state of the USV navigation. It distributes the correct functions to the thrusters. The state machine establishes two general states: "Manual Navigation Mode" and "Automatic Navigation Mode."

The "Manual Navigation Mode" state assigns a pre-set numerical value for each motor according to the command of the operator. For example: for "Go forward", it drives 70% of maximum power, and for "Go back", it drives 100% in the opposite direction. The cycle state ends in the "Output values" block. This output connects to the intermediate layer of the hierarchical control architecture.

The "Automatic Navigation Mode" state consists in defining the desired maneuver type. Currently, two are available, and more can be added by adding new blocks. Then functions such as "reference setting", "Compute H_∞", and "Feedback" are executed sequentially to determine the value of the motors using an advanced H_∞ controller published in [8], [24] specifically for this vehicle. The output block is connected to the intermediate layer as in manual navigation mode. The intermediate layer converts the numerical data

FIGURE 8. The graphical user interfaces for monitoring the navigation of the USV *EDSON-J*, the graphs belong to the tests carried out in the VR4 reservoir in Majes - Arequipa with a duration of 2 hours, the interface shows the register of all the data in time.

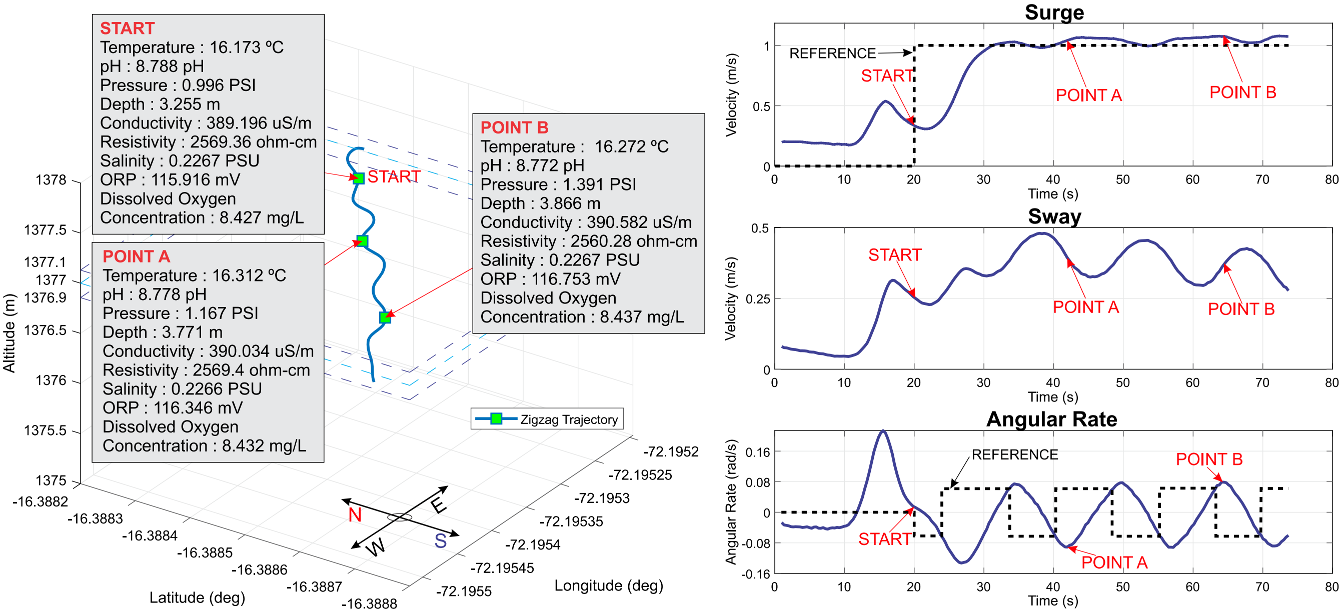

FIGURE 9. Measuring water quality parameters in real-time during zigzag maneuvering in an agricultural reservoir in Majes-Arequipa, together with graphs of the vehicle's surge, sway, and angular rate with the reference signal. Starting point, Point A, and Point B are randomly selected for demonstration purposes.

from the FSM to values from −127 to 127, where −127 is the maximum counterclockwise rotation of the motors, 0 indicates that the motors do not turn on, and 127 is the maximum clockwise rotation of the motors. This layer uses the DC motor driver library and generates the values to connect directly to the driver's serial terminals. The driver and propeller are on each side in the low-level layer. It receives the values from the library in the microcontroller in the intermediate layer and converts the information into a pulse width modulated (PWM) signal. The signal activates the motor driver and generates the DC power signal for the thrusters. The response time is short (<100 milliseconds). The navigation subsystem and hierarchical control architecture end at this level.

A hybrid connection connects both control architectures in the computers. At one end, the "USB" protocol connects to the main computer, and at the second computer, the "UART" protocol. This link provides sufficient bandwidth (12 MBPS)

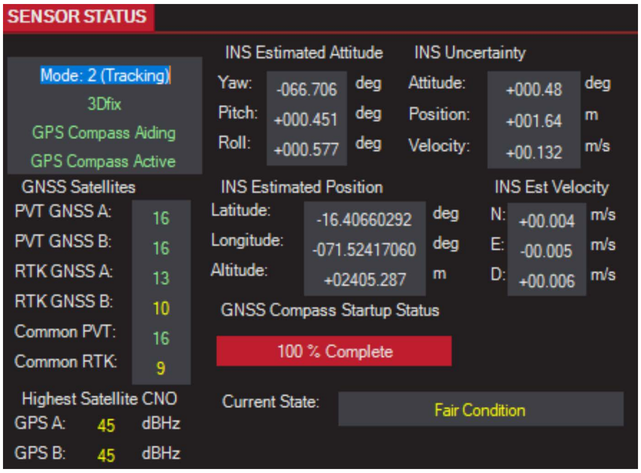

FIGURE 10. INS/GNSS calibration and alignment.

between both computers, where the messages consist in sending commands for interpretation and receiving floating values from the motors to store in the database and display on the interface.

IV. RESULTS

Before the experimental tests, the INS/GNSS calibration runs on the VN-300 microprocessor; there are three steps involving non-tracking, aligning, and tracking. Fig 10 shows the results after a calibration procedure in a visual interface provided by the VN-300 manufacturer. Initial parameters are required by the GNSS antenna baseline, the position of antenna A (offset), and the baseline uncertainty (2.5% according to the user manual [25]). After the calibration, the data are sent to the main computer of the *EDSON-J*.

The testing of the vehicle is performed at the Majes VR-4 city reservoir (latitude: −16,388, longitude: −72,195) in Arequipa-Peru (Fig. 7). The reservoir is used to store excess water temporarily. It is an agricultural region located 100 km from the laboratory; the USV is easily towed to the test site, and the assembly and disassembly take 30 minutes. The mission aims to:

- Validate the methodology used for developing the vehicle and testing the system architecture.
- Obtain field dynamics data to analyze and tune the vehicle model.
- Test the propulsion force of the vehicle.
- Provide water quality data to the agency responsible for managing the city reservoir.

The mission lasted two hours, consuming 30% of the total energy at an average cruise speed of 1 m/s with a total weight of 250 kg. It exceeds the 5 hours of autonomy proposed in the design requirement. During the tests, the correct operation of the subsystems was verified, mainly the control and navigation subsystems. Manual navigation was used to verify the robustness of the wireless link and latency (telecommunications subsystem), propulsion power (peripheral and navigation subsystem), and data reception in the GUI and database (monitoring and storage subsystem). Fig. 8 shows navigation data such as command, percentage of activation in each motor, body velocity, Euler angles, latitude, longitude, altitude, angular velocity, linear acceleration, and universal coordinated time (UTC) in each sample. This interface significantly helped to control the performance in the tests. The data and videos of the experiments are shared in the link https://github.com/jorchmch/EDSON-J-USV.

Water quality data can be obtained from any point in the mission location. The main advantage of this vehicle over others is the easy accessibility to places that can often pose a risk for human access. Some USVs of similar size are highly expensive and are developed by the private sector, but *EDSON-J* allows large payloads and easy integration into the system for remote monitoring in risk areas.

During the tests, due to the morphology of the city, strong winds generate considerable currents in the reservoir. With these disturbances, maneuvers are performed to obtain water quality data at different points. Fig. 9 illustrates the Zigzag maneuver. It shows the vehicle location at any 3 points (Start, A, and B). At all times, the parameters of the payload subsystem are known, such as temperature, pH, pressure, depth, conductivity, resistivity, salinity, oxidation-reduction potential (ORP), and dissolved oxygen. Also, in Fig. 9, three curves of the USV dynamics are observed; the surge rate is the change of position concerning the X-axis of the body, the sway rate to the Y-axis, and the angular rate is the rate of rotation concerning the center of the body. This maneuver works mainly by a secondary computer (Control and navigation subsystem) and, in particular, the "Automatic Navigation Mode" state, which contains the functions of reference configuration, calculation of the optimal controller H_∞, and feedback correction. Fig. 9 shows the reference signals in Surge and Angular rate with dotted lines. This maneuver is typically performed in the development of manned and unmanned surface vehicles. It is suitable to perform monitoring large extensions of water.

The circular maneuver in Fig. 11 is performed in an open loop for more than 6 minutes; the effects of environmental scenarios are appreciable, such as the disturbance in the lake and high winds that eventually move the vehicle to a lateral displacement. In the steady states, the surge velocity is 0.9 m/s, the sway velocity has an oscillatory behavior due to environmental wind, and the yaw rate is 0.125 rad/s. At the start and the end of the experiment, transitory behavior is observed due to the switch between "manual" and "automatic" operation modes defined in the architecture. The left 3d image is the location of the multi-parameter sonde and the data captured in three specific points (the start, point A, and the end). The data logger collects samples every 1 second.

The flexibility and scalability of the system were proved by introducing repetitive and additional sensors to the instrumentation sonde, using a different protocol for these new peripherals. Regarding computational cost, the executed tasks were measured using the system monitor on Linux, and the demand of resources is still low, concluding that more advanced algorithms may be added, such as vision-based control, path following guidance, and obstacle avoidance,

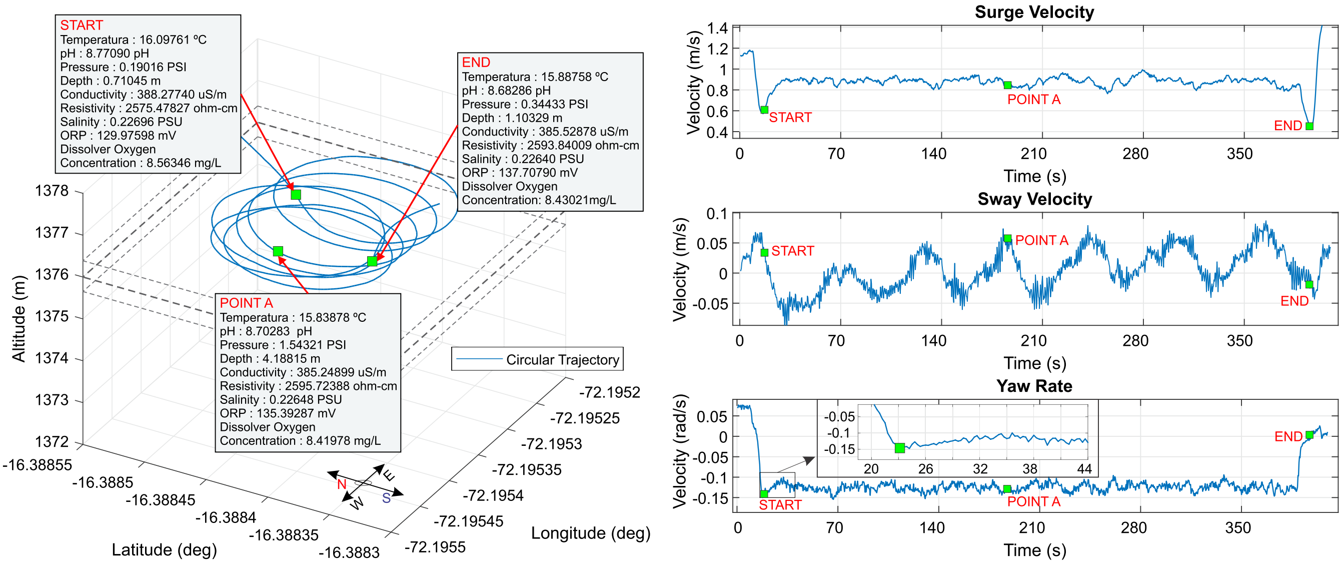

FIGURE 11. Circular trajectory of the vehicle in open loop control system.

with data captured by stereo cameras. Other missions may require another kind of sensor to measure different water quality conditions. For example, Chlorophyll A is required to detect photosynthesis and the presence of life.

The *EDSON-J* architecture is hybrid. Inspired by the works of [17] and [16], the worked methodology is validated, and the advantage of the system for payload capacity is perceived. The architecture presents adequate adaptability, agility, and reconfigurability for different onboard instruments. In addition, for official water quality survey reports, certified measuring instruments are required, and sometimes the size and weight properties cannot be covered by a small USV. In contrast to locally built USVs in Peru [26], it has greater versatility to support payloads and superior positioning accuracy than a commercial global positioning system (GPS) module. This vehicle is relatively cheaper than the one produced by the private sector. Its use can be extended to study water quality in different cities in southern Peru. The other validated contribution of this architecture is to provide measurement and estimated variables to the *EDSON-J* robust controller. The whole methodology is targeted to support research in unmanned vehicles with linear parameter variant and path following guidance approaches [24].

V. CONCLUSION

This paper presents a hybrid control architecture methodology applied to an unmanned surface vehicle. EDSON-J vehicle is designed for water quality monitoring reservoirs, lakes, and coasts. The main objective is to create a good distribution and configuration of the platform that allows water quality monitoring, facilitates the attachment of new payload instrumentation, increasing flexibility and scalability for different missions and scenarios. The specifications and requirements consist of system engineering concepts, such as risk management, design flexibility, logical decomposition, functional classification, verification, integration and validation, and technological plan. These are validated with the proposed methodology and through tests performed in an agricultural water reservoir of 50 000 m^3 water capacity. The vehicle recorded 1138 samples related to water quality parameters during the 2 hours of the monitoring mission. It showed an acceptable level of technological maturity and provided a stable and reliable basis for its continuous development. Further works are related to validating the guidance with obstacle avoidance, considering cameras and additional payload instrumentation. Moreover, a V-Model design methodology can be considered for further comparison.

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