An amphibious drone for aerial, surface, and underwater assets and environmental remote monitoring to support the sustainability of unmanned offshore converted platform

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The PlaCE project [R1] aims at promoting, for the first time at Italian national level, technologies and solutions for the eco-sustainable reuse of offshore platforms at the end of their production phase. Several applications were considered, including the production of renewable energy necessary for the platform's activity, the monitoring and evaluation of environmental parameters and ecological quality, the development of integrated and multifunctional systems for maintenance. PlaCE explored and combined innovative technologies and solutions for the reuse of existing assets, focusing on the processes of acquisition, analysis, and management of environmental data. In this context, different remote monitoring solutions were investigated to assess the environmental impact and sustainability of the conversion of offshore assets. A part of these solutions concerns the installation of an innovative monitoring system on the seafloor able to acquire in real time a wide array of environmental parameters of interest [R2].

Fig. 1 - The Amphibious Drone at sea.

On the other side, robotic mobile solutions that allow in a versatile way to monitor the activities as a whole by acquiring environmental data and parameters in the entire area of interest have been explored. The solution presented in this paper concerns the development of the proof-of-concept of an Amphibious Drone which, operating in complete autonomy and having the platform as an operational base, allows continuous and versatile monitoring of the area affected by the platform conversion operation. The Amphibious Drone has been designed and developed by Neabotics. This paper illustrates the system architecture and its main components, and the performances demonstrated through a test campaign. The tests concerned the seakeeping performance of the drone conducted at the towing tank facility of the University of Naples Federico II at Industrial Engineering Department, acceptance tests in a protected environment carried out at a sport fishing center in Marigliano (NA) and, finally, sea tests carried out at the Turtle Point of the Anton Dohrn Zoological Station in Portici (NA).

SYSTEM ARCHITECTURE

The goal of the Amphibious Drone is to operate autonomously without the involvement of a human operator or direct control from a ground

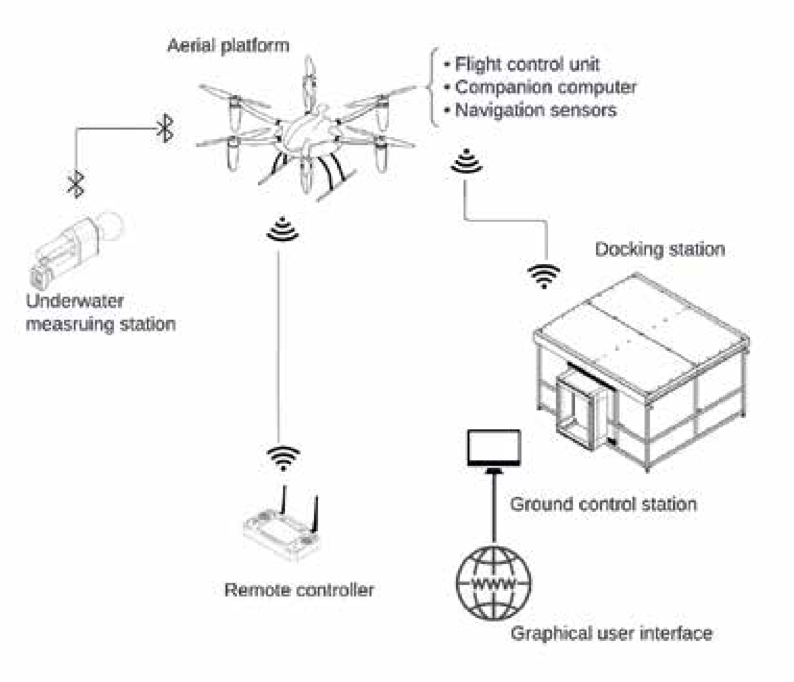

Fig. 2 - System architecture.

station for long term deployment. To support the mission, a set of heterogeneous modules cooperating to set up and execute the mission of analyzing the gathered data have been developed. These modules and their connection are shown in the System Architecture depicted in Fig. 2. It consists of three main modules: the Aerial Platform system that transports the measurement tools, the Docking Station where the Amphibious Drone rests and the Underwater measuring station containing the set of sensors used to gather data from the underwater marine environment. Similar systems have been proposed, like Error: Reference source not found able to sample the water during the flight. Of course, this solution is not suitable for long term inspection (due to the low duration of the battery) or for deep water analysis.

To guarantee protection to the Amphibious Drone, during the waiting time between the different missions and to be covered from bad weather conditions, the Docking Station has been designed. Here, a battery recharge mechanism ensures that the batteries are recharged between each mission and a ground computer is installed to retrieve the state of the Drone and the data gathered during the mission. These data are available through Graphical User Interface accessible as a web page by personal authentication. The same interface can be used to schedule the inspection missions or to require direct actions to the Aerial System.

The system flight is enabled by the onboard autopilot, also known as Flight Controller Unit (FCU). This unit is directly connected to the Drone's motors, and it implements a set of functionalities to translate position control input (the trajectory of the aerial vehicle) into rotors' velocities. In addition, all the stabilization of the platform and all the safety layers allowing the recovery of the platform and its return to the Docking Station in case of faults of the navigation sensors or any other unexpected situation are implemented in the FCU.

Even though the system is thought to work autonomously, a human operator can control the aerial vehicle with a Remote Controller through a radio link. When it is manually operated, the FCU directly responds to the input received from the remote Remote Controller. The communication range of the radio link is 10 km. This range can be restricted by the environment, in case of obstacles between the Radio Controller and the Drone. Different sensors are carried on the Aerial Platform to perform the water monitoring task. They can be divided into aerial measurement sensors (a colored camera and a multi-

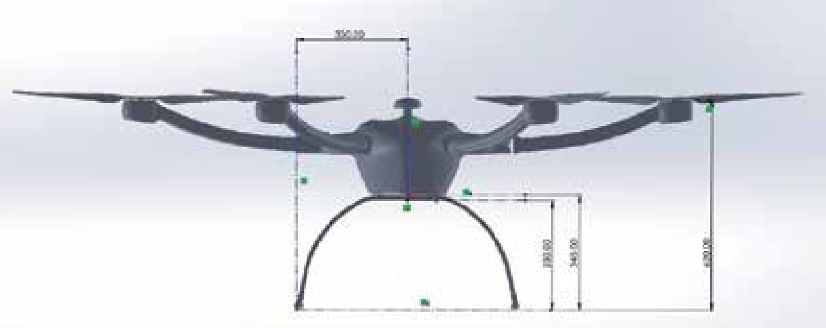

Fig. 3 - Hexacopter frame.

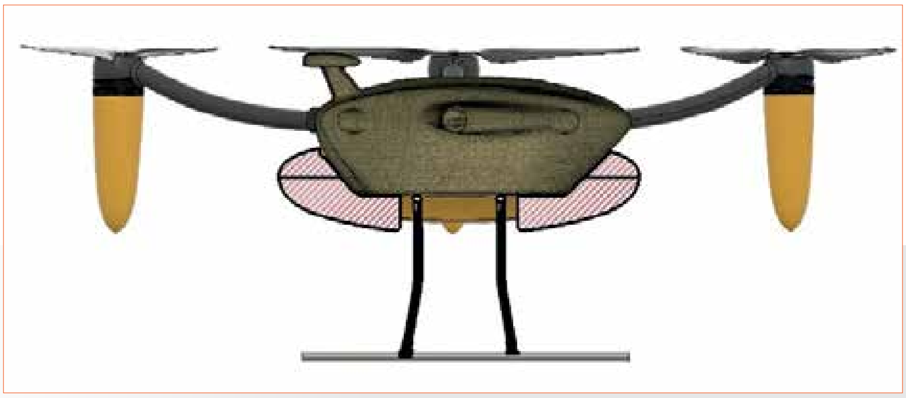

Fig. 4 - Floating system

spectral sensor) and underwater inspection sensors.

The Drone's autonomous behaviors and its interaction with the Ground Control Station (GCS), hosted by the Docking Station, are implemented thanks to the presence of an onboard companion computer physically connected to the FCU. The computer runs a standard distribution of the Linux Operating System. From this computer, the inspection missions are configured and executed at a given time. Besides this, the companion computer enables communication with the GCS. It is worth noticing that communication between these two modules is not available when the Drone flies far from the recovery station. All the data collected during the mission and all the data set from the human operator are exchanged only when the communication link is available. The Drone system, the subsystems and their integration are detailed in the following paragraphs.

Aerial Platform

The Aerial Platform consists of a planar hexacopter in carbon fiber material. All the components needed to control the Drone (i.e., batteries, computer and similar) are stored in a central hollow that guarantees the IP66 enclosure. Even though the motors are waterproof, as can be seen from Fig. 3, the propellers of the Drone are distanced with respect to its center of mass. In this way, safety is guaranteed during splashdowns because the motors are taken far from the water. The diameter of the platform is 158 cm, its weight is 5 kg. Finally, the platform is equipped with 28-inch propellers to improve efficiency and flight autonomy. In this setup, the total flight time is assessed to be 50 min.

Avionics

The system's Avionics consists mainly of two elements: the autopilot and the onboard computer. The autopilot is based on the open-source board PixHawk. The PX4 control stack has been selected as autopilot firmware. The adopted autopilot is characterized by different sensors used to improve drone localization and stabilization during the flight. Three Inertial Measurement Units (IMUs) are installed for fault tolerance purposes. Each IMU is endowed with 10 Degrees of Freedom (DoFs) and consists of an accelerometer, a gyroscope, a magnetometer, and a barometer. The autopilot is connected to the six motors and allows the control system to be in different modes. In particular, the following control modes have been considered and tested:

- stabilized: a manual control mode the Drone uses the inertial sensor to align the propellers with respect to the level of the horizon,
- the position control mode: the Drone uses an estimation of its position in a fixed frame to regulate its overall position,
- the offboard control mode: where the Drone accepts control input from the onboard computer.

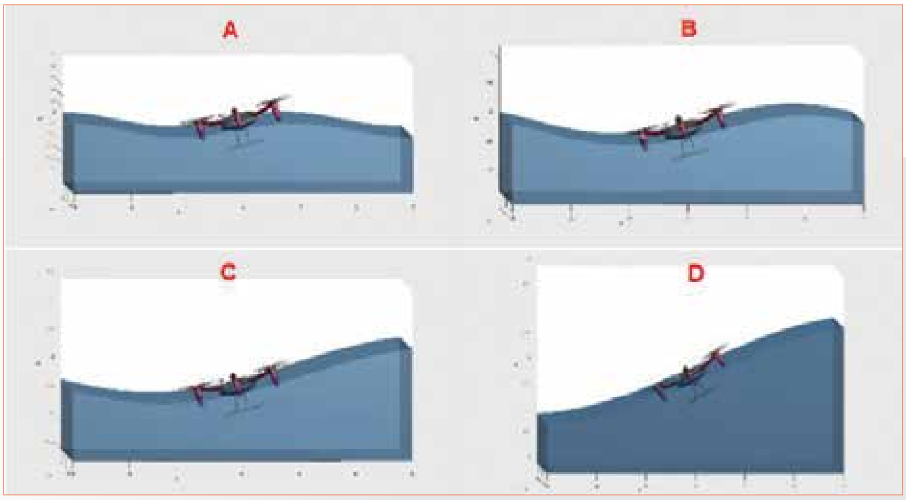

Fig. 5 - Simulated Drone reacting to different waves.

Case	Amplitude [cm]	Period [s]	Wavelength [m]	Steepness [%]
A	12.5	1.5	4	3.6
B	25.0	2.0	6	4.0
C	50.0	2.5	10	5.1
D	100.0	3.0	14	7.1

Tab. 1 - Different operating conditions tested in the simulation environment.

In this context, the system avionics exploits two GPS sensors to estimate the Drone's localization. At the same time, to improve the localization and therefore, the overall platform positioning during the flight, a Real-Time Kinematic (RTK) GPS has been considered. This kind of device uses a base station along with the GPS receiver placed on board the Drone to overcome the standard GPS positioning error.

As for the onboard computer, a lightweight computer equipped with an ARM processor has been adopted. This computer is physically connected to the Drone autopilot with an USB cable exploiting a serial communication protocol. Telemetry data (i.e., position, attitude, operating mode) are received from the autopilot, while the desired position of navigation actions (i.e., takeoff, land and similar) are sent to the autopilot based on the current mission. The communication system uses MAVLink Error: Reference source not found protocol, a standard de facto of the autopilot messaging system for autopilots.

As shown in the architecture sketch (Fig.2) the Drone communicates with the GCS. This is made through a standard wireless connection, by means of a WiFi Access Point. When the drone flies close to the GCS, or it is in the recovery housing, the companion computer is connected to GCS network. Once connected, a set of scripts are used to store/exchange information between the station and the Drone. In this context, a Python 3.7 scripting language is used as the programming language. In this kind of application, the critical issue is the availability of the connectivity between the GCS and the Drone's companion computer. The ZeroMQ (zmq) Error: Reference source not found library has been adopted to implement robust intra-process communication also with a remotely distribute software architecture, allowing, data sharing among the different clients in an asynchronous way.

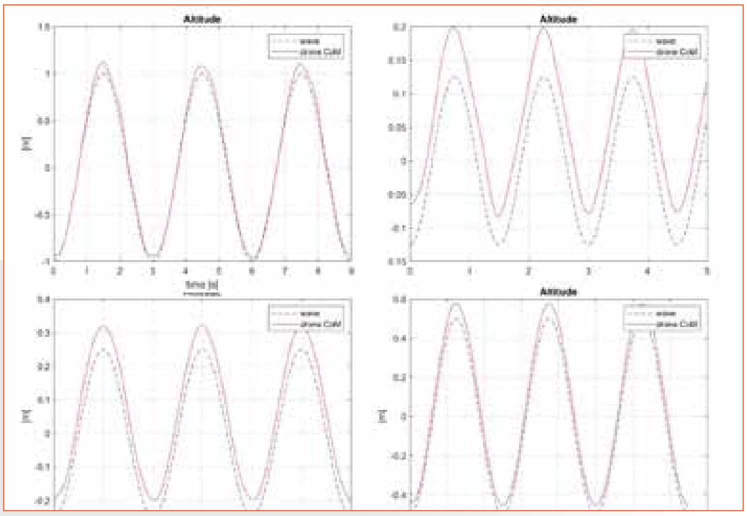

Fig. 6 - Vertical component of the translational motion of the Drone (blue and dotted) and the wave (red line).

Floating System

To carry out the task, the Drone must be able ditching on the water surface deploying the inspection probe at a desired water depth. During the underwater inspection, the Drone must be able to float reacting to the waves. For this reason, a Floating System has been designed and installed on the Aerial Platform. The Floating System consists of two main modules. A large central module is to compensate for the overall weight of the Drone and six floating cones are placed down the motors to stabilize the attitude of the Drone also in presence of high and irregular waves. It has been designed to completely fit the external chassis of the Drone and consider the vehicle's aerodynamics. As for the floating cones, their shape has been designed to reduce turbulence without occluding the propellers' airflow. Fig. 4 shows the Aerial Platform with the Floating System. To validate the design of the Floating System and the overall capacity of the Drone's seakeeping capability, a set of numerical simulations have been performed in a Matlab environment. Different wave amplitudes at different periods have been simulated to assess the capacity of the Drone to stabilize over the water surface. A set of frames taken from the simulation, during its opera-

Fig. 7 - Multispectral camera and gimbal waterproof housing.

ting condition are depicted in Fig. 5. The tested conditions are summarized in Tab.1.

The vertical displacement of the Drone compared withwave amplitude are reported in the four cases in Fig. 6. These results demonstrate the capacity of the Drone to tackle the considered water conditions.

Aerial Measuring System

One of the goals of the Aerial Platform is to monitor sea environmental conditions. The Drone is equipped with a multispectral camera to evaluate the heat of the water and the presence of pollutants. This camera is attached to a 2 DOF gimbal (pan and tilt unit) that is used to stabilize and direct the view during the flight.

Fig. 8 - Underwater measuring station.

In addition, to guarantee the protection of the camera from water, it has been stored in a waterproof, transparent housing as shown in Fig. 7.

This multispectral camera is equipped with an independent GPS sensor. In this way, the images taken during the navigation are geo-referenced. The captured images are sent to the companion computer through a WiFi connection. In addition, the selected multispectral camera is equipped with a PAR sensor, in order to regulate the exposure of the images based on the air luminosity. Finally, the aerial measuring system contains a visual High Definition camera that is streamed on the GUI and on the radio controller of the operator. This camera can be used to see the inspection scene or what surrounds the aerial vehicle.

Underwater Measuring Station

The Underwater Measuring Station has been designed to store the underwater inspection probes and it is hosted by the Aerial Platform. Once ditched, the inspection probe is rolled out to the desired depth. The depth, along with the measuring time, is specified as parameter of the inspection mission and can be set from the GUI when a new mission is a set-up or requested. The station is placed close to the transparent dome in which the cameras are inserted, and it has been designed with a bell shape to store the inspection tool. To allow the descent of the inspection probe, a rod reel has been installed in the upper part of the measurement station (in red in Fig. 8). The reel is controlled with a servomotor, connected to an integrated control board. To decouple the effects of the water current on the aerial system, the inspection probe is attached to the reel with a line and supports up to 70 meters of depth. The station is designed to be waterproof.

The core of the water inspection system is represented by the inspection probe, shown in Fig. 9. This probe contains a set of sensors commonly used to assess the quality of the sea water directly in place. The sensors are encapsulated into a waterproof container along with a microcontroller, used to gather all the data generated during the water inspection and communicate with the companion computer of the aerial platform. The following sensors are installed: flurometer, PAR (Photosynthetically Active Radiation), CTD (Conductivity, Temperature, Depth), PH, Visual camera.

The controller implements the protocol of all such sensors and during the inspection, the data of these sensors are collected at a fixed interval The Underwater Measuring Station has an independent battery for the power supply of all the sensors and the control board. The recharge is made by a wireless recharge module that receive the power supply from the Aerial Platform. In this context, the visual camera is used to acquire some shots during the underwater inspection rather than a live stream. One shot for second is considered. The communication between the Aerial Platform and the Underwater Measuring Station relies on Bluetooth communication protocol. It is worth to notice that the inspection probe is overall autonomous in its mission, and it is completely controlled by the onboard micro controller. It just receives the command to start an inspection task along with the mission duration.

Docking Station

To keep safe the Aerial Platform during the non-mission time, a Docking Station is designed. To goal is to place this station on an offshore site, to charge the Drone's batteries, upload the mission data and wait for the start of a new mission. The design of the station is depicted in Fig. 10. The figure is shown in its configuration with the two hold doors opened. When the Drone must take off or is close to land, the two doors are open, and a vertical lifting pane drives the Drone to the bottom/upper part of the recovery site. Before the descent of the vehicle on the lift panel, its propellers are aligned to by an automatic propeller alignment system. Additionally, four bars independently actuated drive the feet of the vehicle towards the centre of the lifting panel (Fig. 11). In the automation of the Docking Station is controlled by a dedicated an electric panel. The Docking Station hosts also the server computer running the web based Graphical User Interface.

Software Architecture

The overall Software Architecture is depicted in Fig. 12. Salient data are exchanged between the different modules of the Software Architecture due to wired or wireless communication channels. The operator can use the Remote Controller to directly command the position of the Drone. These data are sent to the Drone's autopilot that provides the vehicle telemetry (i.e., the current position, attitude, battery charge and similar). These data are received in the same manner from the onboard computer. This computer is also responsible for receiving data from the Underwater Measuring Station once the inspection mission is completed. This information is sent to the GCS, which stores all the salient information in its database. The inspection probe receives signals informing the start of a new mission. Finally, the GCS makes available the data stored in the database, along with the current state of the aerial vehicle, through the web based Graphical User Interface (GUI).

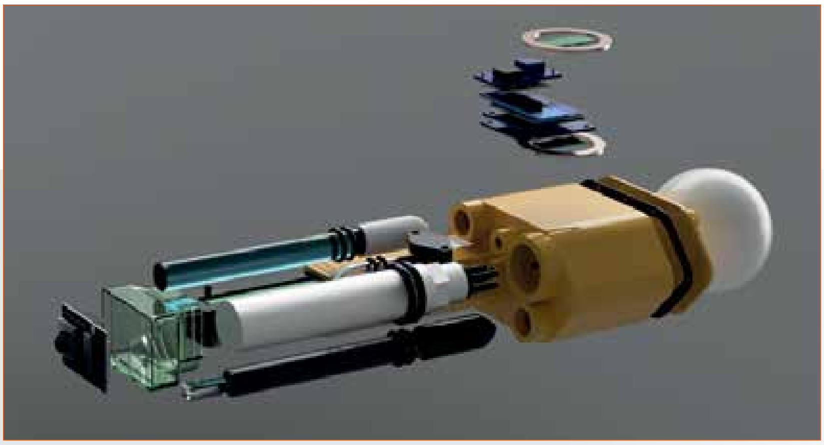

Fig. 9 - Inspection probe.

SEA KEEPING TESTS

The towing tank facility of the University of Naples Federico II located in the Industrial Engineering Department has been adopted to experimentally validate the floating capability of the Aerial Platform. Moreover, due to the low height of the maximum wave height allowed in the tank, a scaled model has been used instead of the actual Aerial Platform (Fig. 13). All the elements taking part in the floating process have been reduced considering a 1 to 3 scale. An onboard calculation unit logs the roll and pitch data during the floating in the generated waves provided by an Inertial Motion Unit mounted onboard the model.

The tank is (147x9x4.2) meters. In the tanks, a dynamometric cart generates waves with a desired altitude. Regular waves have fixed altitudes for

Wave type	Significant Height Hs [cm]	PeriodT [s]	Wavelength [m]	Steepness [%]
Irregular	48	1.485	3	14.0
Irregular	45	1.856	5	8.4
Irregular	25	1.856	5	5.0
Irregular	27	1.880	6	4.9
Regular	15	1.732	5	3.2
Regular	21	1.732	5	4.5

Tab. 2 - Conditions of the floating test experiments in the towing tank of the University of Naples Federico II.

Fig. 10 - The Docking Station.

periods. To assess the floating capability, different wave conditions have been tested, with both regular and irregular waves: irregular waves from 25 to 50 cm of altitude with 1.8 seconds of the period each to check the model behaviors at different wave steepness.

For each test, the scaled model has been capable of following the wavy way, maintaining the propellers over the level of the water. This is enough to assure safe takeoff from the water, after the floating phase. In Tab. 2, the different conditions of the wave type and its period tested in the towing tank are reported.

Among the different tests, in results on the most significative test are reported. In this context, a set of waves with a significant wave (Hs) equal to 48 has been generated with a period of 1.485.

The altitude of the waves is reported in the graphics depicted in (top), while the attitude of the model, namely the pitch and roll, is reported in (bottom).

Considering the attitude of the model during the floating, it's worth noticing that the model can stay stable on the water surface (i.e., the pitch orientation during the test never exceeded critical values).

FIELD TESTS

The inspection system at work has been tested at the Stazione Zoologica Anton Dohrn located in Portici, Naples, in July 2022. The test site is shown in Fig. 15. The formation of the site allowed the location of the docking station close to the sea, at a higher altitude with respect to it, recalling the conditions of a realistic operative environment (the offshore platform). During the tests, different missions have been proven consisting of a set of planned segments connecting different waypoints and water inspection tasks. All the tests contain the following actions:

- Takeoff from the recovery station.
- Navigation and eventually aerial inspection with the multispectral camera.
- Underwater inspection reaching at different depths.
- Return to land in the recovery station.

There missions have been considered and have been pre-planned and stored in the onboard computer of the aerial system using the GUI available on the private webpage.

In particular, the first mission consisted of two segments and one underwater inspection task. The actions performed during this mission are listed in the following:

- Takeoff
- Navigation with multispectral inspection
- Underwater measurement at 4 meters depth
- Land in the docking station

The total mission time was 2.54 minutes, in which 288.2 meters have been covered. The maximum speed has been commanded to be 20.5 km/h with a 12.8 deg of tilt angle.

The second mission has been planned with five segments and

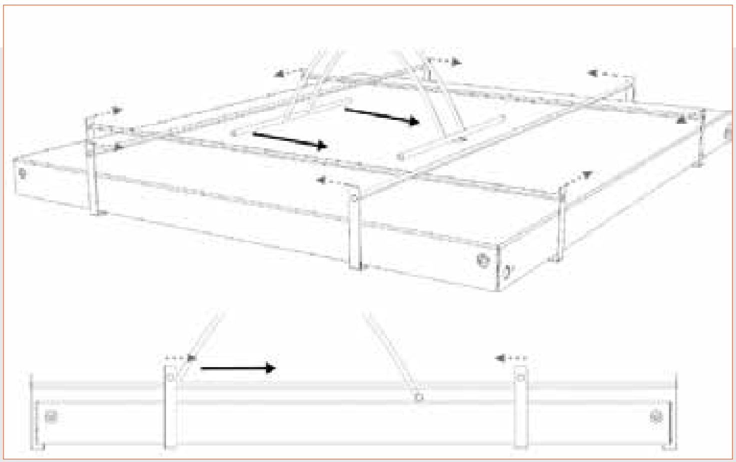

Fig. 11 - Alignment System of the Docking Station.

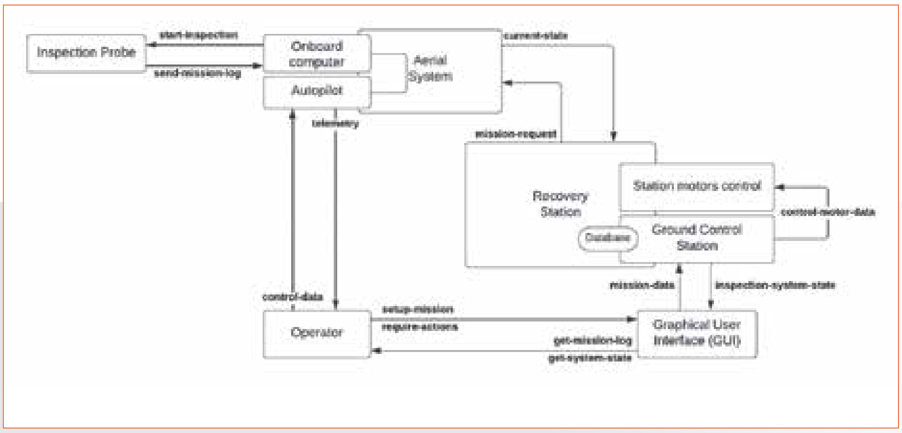

Fig. 12 - Software architecture.

four underwater inspections. The list of actions performed in this mission are listed in the following:

- Takeoff
- Navigation with multispectral inspection
- Underwater measurement at 4 meters depth
- Navigation with multispectral inspection
- Underwater measurement at 4 meters depth
- Navigation with multispectral inspection
- Underwater measurement at 4 meters depth
- Land in the docking station

The total navigation time has been of 6 minutes, while 420 meters have been covered. Finally, the third mission has been planned with four segments, following this list of actions:

- Takeoff
- Visual inspection of the river
- Navigation with multispectral inspection
- Underwater measurement at 4 meters depth
- Navigation with multispectral inspection
- Underwater measurement at 4 meters depth
- Navigation with multispectral inspection
- Underwater measurement at 4 meters depth
- Land in the docking station

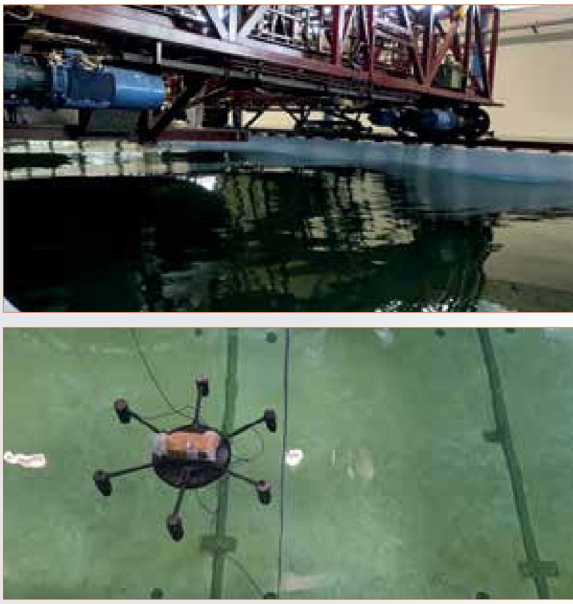

Fig. 13 - Aerial platform model (1:3) (Top). Model in the tank (Bottom).

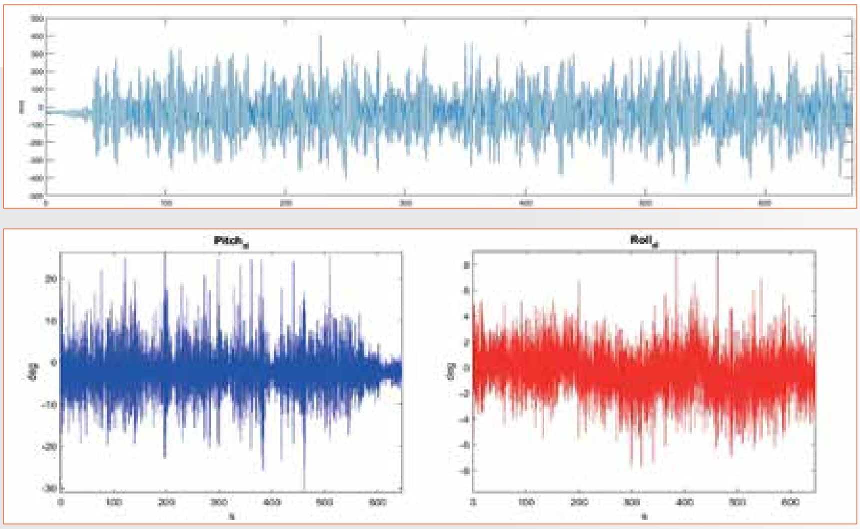

Fig. 14 - Top: wave profile during one test. Roll (left) and pitch (right) angles of the mockup used to validate the floating system during worst conditions test.

The total flight time has been 4.49 minutes in which 410.9 meters have been covered. Data collected during the first mission are detailed in the following. In this context, the trajectory executed during the mission is depicted in Fig. 16, where the GPS data available on the autopilot's logs are superimposed on the satellite image of the test site. On the same data, three different segments can be distinguished, the takeoff (1.1), the multispectral data acquisition path (1.2) and the landing on the sea and water analysis (1.3). The complete mission duration was 1.35 minutes, and the maximum altitude displacement, from the takeoff location to land on the water altitude was 10 meters. The overall distance covered by the platform was 154.6 meters, while its average speed was 5.7 km/h (with a maximum speed of 17 km/h). An example of the images captured from the multispectral camera during this mission are reported in Fig. 17. Each image of this camera represents an

Fig. 15 - Field test site.

Fig. 16 - Trajectory executed by the aerial platform during the mission. Three segments can be distinguished.

image acquired at a particular wavelength band, providing different information of the scene.

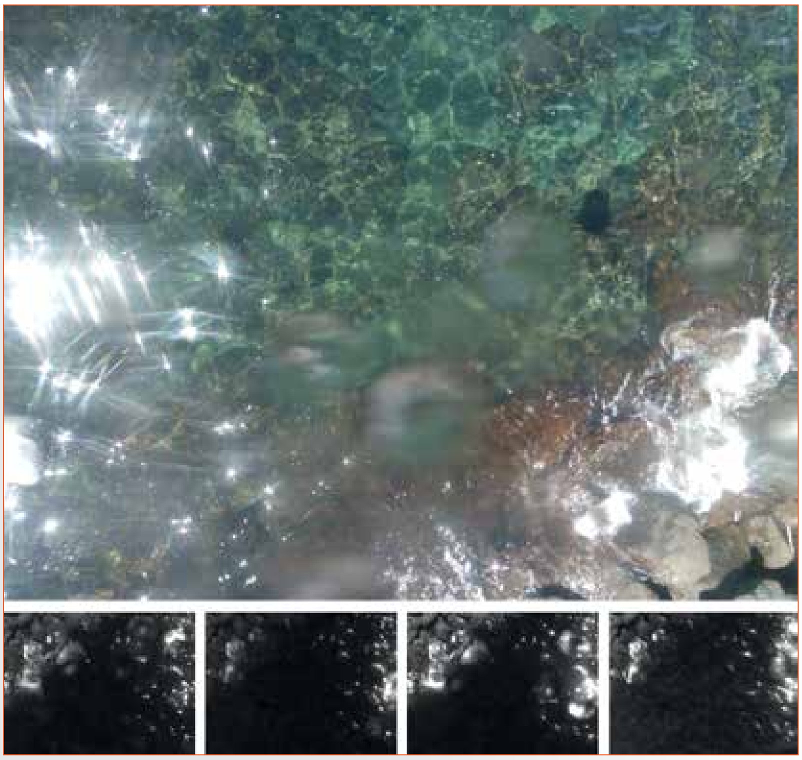

Fig. 17 - Images from the multispectral camera: RGB, GRE, NIR, RED, REG.

Finally, data collected during the marine inspection task are reported in Fig. 18. Here the data received from the sensors contained in the inspection probe are associated with the depth of the probe (the blue line in the graph). The collected data are:

- PAR-water: represents the Photosynthetically Active Radiation of the water, that is the amount of sunlight or ambient light that diffuses through the water compared to surface light. As expected, the PAR value decreases inversely proportional to the depth of the sensor.
- Temperature: represents the temperature of the water. It remains almost constant during the descent of the probe.
- PAR-air: it is the PAR of the air. Considering the low permanence time of the UAV during the inspection, it remains almost constant.
- PH: it's the potential of hydrogen of the water, that is, its acidity.
- Fluor: represents the fluorescence of the water.
- Salinity: it's the salinity of the water.

executed by the aerial platform during the mission. Three segments can be distinguished. The collected value during the underwater inspection mission, collected at the maximum depth (about 4 meters) are reported in Table 3.

CONCLUSIONS

This paper introduces a novel aerial system designed for surface, aerial, and underwater inspection. At the heart of the system is an amphibious drone that can fly over water and land on it or float on the surface. During the floating phase, the drone employs an underwater inspection probe to assess water quality. When not in use, the system returns to a docking

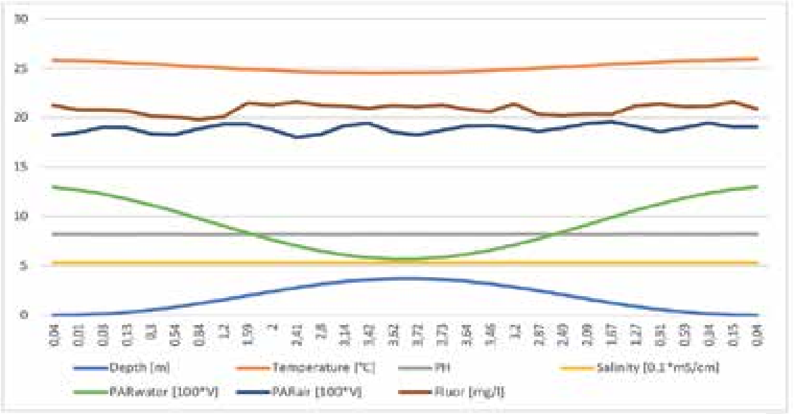

Fig. 18 - Measures from the inspection probe during the water descent.

station where its batteries are recharged, and mission logs are downloaded.

To ensure the system's effectiveness, it has undergone various tests. The float capability was assessed using Matlab simulation tools and through a mock-up in a controlled laboratory environment.

Additionally, the complete system was field-tested, and various inspection missions were carried out.

The system's aerial platform characteristics, such as flight performance, are presented in Table 4.

Data	Value
Temperature [°C]	24.5
Depth [m]	3.73
PH	8.2
PAR (water / air) [V]	0.057 / 0.18
Chlorophyll [mg/l]	21.06
Salinity [mS/cm]	53.51

Tab. 3 - Water data at maximum inspection depth during collected during a field test.

Data	Value
Weight [kg]	23
Payload [kg]	8
Max. tilt angle [deg]	67
Max. speed [km/h]	75
Max. hovering flight time [m]	31.2
Onboard current [A]	24.04
Tension [V]	43,36

Tab. 4 - Aerial vehicle specifications.

REFERENCES

[R1] https://bluegrowth-place.eu/

[R2] Zugno F., Schiavon R., Zanino I., Alessi A., Giuggioli A., Malkowski A., Tedaldi M., Di Vito L., Dell'Anno A., "PlaCE - A case study of an offshore asset conversion for multiple eco-sustainable re-use in the Adriatic Sea", *OMC Med Energy Conference and Exhibition, Ravenna*, Italy, 28th Sep. 2021

[R3] Ragib Ishraq Sanim K. *et al.*, "Development of an Aerial Drone System for Water Analysis and Sampling," *2022 International Conference on Unmanned Aircraft Systems (ICUAS)*, Dubrovnik, Croatia, 2022, pp. 1601-1607, doi: 10.1109/ICUAS54217.2022.9836122.

[R4] Koubâa A., Allouch A., Alajlan M., Javed Y., Belghith A. and Khalgui M., "Micro Air Vehicle Link (MAVlink) in a Nutshell: A Survey" in *IEEE* Access, vol. 7, pp. 87658-87680, 2019, doi: 10.1109/ACCESS.2019.2924410.

[R5] Lauener J., Sliwinski W., "How to design & implement a modern communication middleware based on ZeroMQ", *16th International Conference on Accelerator and Large Experimental Physics Control Systems*, Barcelona, Spain, 8 - 13 Oct 2017.

KEYWORDS

PlaCE Project; robotic mobile solutions; robotic technology; amphibious drone; A/RPAS;

ABSTRACT

The PlaCE project aims at investigating technologies and solutions for the eco-sustainable reuse of offshore platforms at the end of their production phase. In this context, robotic mobile solutions that allow in a versatile way to monitor the activities by acquiring environmental data and parameters in the entire area of interest have been explored.

This paper presents a solution achieved through the development of the proof-of-concept of a robotic technology concerning a hybrid Autonomous / Remotely Piloted Aircraft System (A/RPAS), hereinafter referred to as Amphibious Drone, operating in complete autonomy and having the platform as an operational base. The Amphibious Drone is developed to cover the entire area of interest surrounding the platform being converted, with the ability to carry the measuring instruments and probes in aerial overflight for monitoring the sea surface and the surface structures as well as ditching to deploy a sensors-equipped probe for measuring underwater parameters along the water column. A wide range of probes and instruments have been integrated into the system such as multispectral camera, Photosynthetically Active Radiation (PAR) probes, Conductivity-Temperature-Depth (CTD) probes, etc. for the analysis of oceanographic and biological parameters of the marine ecosystem. The management of the Amphibious Drone, as regards the shelter between missions, battery recharging, data exchange, required reconfigurations and missions scheduling is carried out from a specially designed Docking Station. The PlaCE project is co-funded by the European Union within the projects "PON Ricerca e Innovazione 2014-2020".

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