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Oil Spill Mitigation with a Team of Heterogeneous Autonomous Vehicles

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Abstract: This paper presents the implementation of an innovative solution based on heterogeneous autonomous vehicles to tackle maritime pollution (in particular, oil spills). This solution is based on native microbial consortia with bioremediation capacity, and the adaptation of air and surface autonomous vehicles for in situ release of autochthonous microorganisms (bioaugmentation) and nutrients (biostimulation). By doing so, these systems can be applied as the first line of the response to pollution incidents from several origins that may occur inside ports, around industrial and extraction facilities, or in the open sea during transport activities in a fast, efficient, and low-cost way. The paper describes the work done in the development of a team of autonomous vehicles able to carry as payload, native organisms to naturally degrade oil spills (avoiding the introduction of additional chemical or biological additives), and the development of a multi-robot framework for efficient oil spill mitigation. Field tests have been performed in Portugal and Spain's harbors, with a simulated oil spill, and the coordinate oil spill task between the autonomous surface vehicle (ASV) ROAZ and the unmanned aerial vehicle (UAV) STORK has been validated.

Keywords: oil spill mitigation; autonomous vehicles; bioremediation; cooperative intervention; multi-robot; autonomous surface vehicle; unmanned aerial vehicle

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1. Introduction

Marine oil spills have a considerable economic and ecological impact on the ecosystem of marine life. Incidents with oil spills occur with some regularity during the exploration, production, and transport of petroleum products [1]. Between 2010 and 2023, there were 90 spills with 7 tonnes or more, resulting in 192,000 tonnes of oil spills in the environment, with 91% of this amount spilled in 32 incidents alone [2]. Such incidents require immediate, simple, effective, and eco-friendly actions to minimize environmental damage. This level of importance in having a fast intervention is detailed in Figure 1, with satellite radar images from Copernicus Sentinel-1 over the Mediterranean Sea, north of the French island of Corsica, after a collision between two merchant ships. The first radar image shows that the oil spill was about 20 km long. Twelve hours later, imagery from the same position shows that the oil spill had lengthened to about 35 km. And 24 h later, the spill had grown to about 60 km long. Therefore, it is clear to us that there is a need to work on autonomous solutions that allow intervention in the first hours of the oil spill to contain the spread and, at the same time, to start the mitigation process.

First-line responses typically include physical (e.g., controlled burning; absorbing) and chemical (e.g., dispersing) oil removal, largely constrained by maritime conditions. Though these treatments are essential to control the diffusion and drift of oil rapidly, they are unsuitable for ecological restoration. Using microorganisms with a natural capacity to degrade petroleum is highly advantageous in an environmentally friendly process and

allows the decomposition of complex petroleum hydrocarbons [3]. The success of bioremediation, to improve petroleum removal and reduce clean-up time and cost, relies on two major approaches: (i) the addition of nutrients to stimulate the growth of the microorganisms that break down oil (biostimulation) and (ii) the addition of pre-grown microbial cultures/consortia to enhance microbial populations (bioaugmentation). This mitigation strategy involves the introduction of microorganisms in the affected environment.

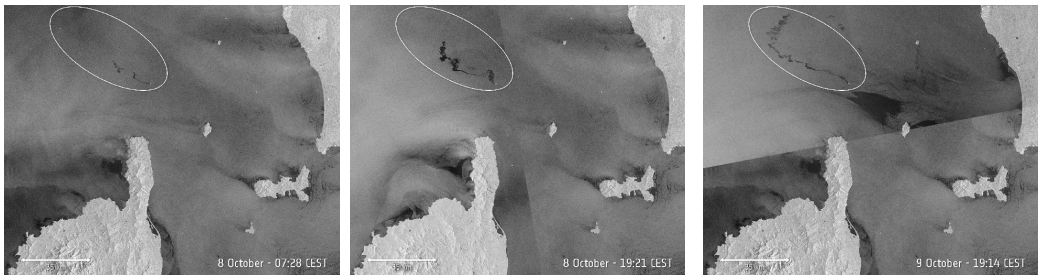

Figure 1. Oil spill incident detected by the Satellite radar images from Copernicus Sentinel-1 in the Mediterranean Sea [4].

The state-of-the-art of oil spill response could be driven by mechanical recovery [5], chemical recovery [6], thermal recovery [7], biological recovery [3], vacuum and centrifuge [8], and solidifying [9,10]. The mechanical approach consists of deploying booms, with the help of skimmers, to store the oil spill in a controlled area. Different skimmers are available, such as ones based on suction, oleophilic materials, or weirs to remove oil from the water's surface. In the second phase, after the oil recovery, it is transferred using pumps and hoses [5]. The thermal response involves a controlled burn of the floating oil [7]. In that case, an ignition device is released from a vessel (or other access points). The ignition is achieved by releasing a burning, gelled fuel from the aerial way (i.e., using a helicopter). The chemical response uses dispersants—chemicals applied to oil slicks to accelerate oil dispersion into the water column. The idea is not to remove the oil from the water, but to limit the amount of oil forming a slick on the water surface by driving that oil into a dissolved phase [11]. Biological recovery consists of the use of native organisms with bioremediation capacity. The innovative solution aims to be environmentally friendly by using this organism to naturally degrade oil spills, avoiding the introduction of additional chemical or biological additives. Another approach is the vacuum and centrifuge method, which uses oil and water to obtain near-purity water. There is a debate about whether the resulting water should be returned to the sea or not due to the amount of oil that could be present at the end of the process. The solidifying of the oil could also be an option. With dry ice pellets and hydrophobic polymers, the liquid oil is solidified into a floatable rubber-like material that allows for a more convenient collection and recycling method.

Technologies that allow a safe, immediate, effective, and eco-friendly operation of oil spill removal, in situ, have been under development in recent years. A specific area that grew from that development was the application of autonomous vehicles for ocean exploration and conservation, with two important projects being developed in 2010: Seaswarm [12] and Protei [13]. The autonomous vehicles designed within the scope of these projects reduce the operational time and protect the health and safety of the cleaning crew by working as an organized fleet or "swarm" of vehicles that rely on ocean-skimming and oil removal techniques. This can be viewed as a limitation of both approaches, since oil considerably impacts the mechanical parts.

This evolution in oil spill mitigation techniques has primarily occurred in hardware development. The research on advanced software-based navigation algorithms still lacks sufficient attention and support. However, some cases are worth mentioning, like the approach developed by [14], which uses a multi-resolution navigation algorithm that seamlessly integrates the concepts of local navigation and global navigation based on the sensory information for oil spill cleaning in dynamic and uncertain environments,

using autonomous vehicles as a single agent. The developed algorithm provides complete coverage of the search area for the clean-up of the oil spills. It does not have the problem of having "*local minima*", which is commonly encountered in potential field-based methods through the adaptive decision-making and online re-planning of vehicle paths. The problem of optimal path following with a team of ASVs and autonomous underwater vehicles (AUVs) for oil plume tracking is discussed in [15], with an approach based on a Genetic Algorithm (GA) to optimize the trajectory of both vehicles. In [16], a cooperative intervention involving UAVs, AUVs, and remotely operated vehicles (ROVs) during the Exercise Cathach is detailed. During the field tests, different research groups demonstrated new robotic systems, sensors, and networking technologies that could be applied during maritime incidents like oil spills.

In this paper, we propose to improve previously described techniques by developing autonomous and coordinated actions that can increase the efficiency of the bioremediation process by deploying microorganisms and nutrients in oil spill-detected areas with a team of heterogeneous robots. Figure 2 presents the concept approach for oil spill mitigation with a team of heterogeneous autonomous vehicles. Each autonomous vehicle is equipped with a release system of microorganisms and nutrients, and is responsible for spreading on top of the oil spill to contain and start the mitigation process. The proposed approach combines two distinguished but, at the same time, complementary research areas: marine biology for the development of native microbial consortia with bioremediation capacity (not addressed in this paper) [17,18], and robotics, in the development of multi-robot frameworks able to ensure the capability of intervention at different levels (air/sea) cost-effectively with a team of heterogeneous autonomous vehicles. This paper is an extended version of the work published in [1,19,20]. The paper is outlined as follows: Section 2 presents the multi-robot approach for oil spill mitigation with a team of autonomous vehicles. The algorithm developed for each vehicle is presented in detail with the respective mathematical formulation. We present both vehicles, ASV and UAV, detailing each vehicle's features and the developments to provide the functionalities to perform oil spill combat. Section 4 details the release systems developed for each vehicle and discusses the requirements imposed on each. Section 5 presents the oil spill simulation environment developed to validate the multi-robot framework for oil spill mitigation and support the field tests. Section 6 presents the field tests performed to validate the developed release systems integrated into the autonomous vehicles and the path planning developed for both vehicles (ASV and UAV). Section 7 presents the remarks and future lines of research to improve oil spill mitigation with a team of heterogeneous autonomous vehicles.

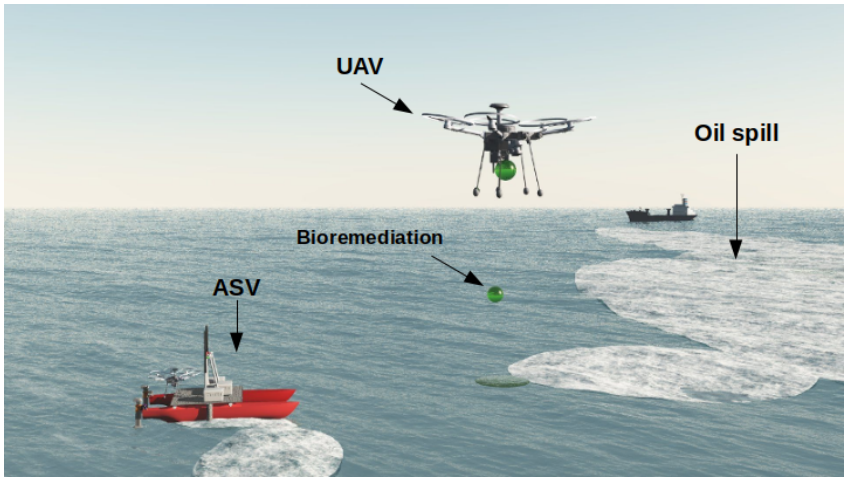

Figure 2. Conceptual approach for multi-robot oil spill mitigation with a team of heterogeneous autonomous vehicles, particularly an ASV and a UAV.

2. Multi-Robot Approach for Oil Spill Mitigation

The in situ bioremediation combat system for oil spill disasters will be performed by a team of unmanned vehicles capable of transport and release of lyophilized bacteria consortia (bioaugmentation) and nutrients (biostimulation) over the oil spill, which will require that each autonomous vehicle have the capability of performing onboard data acquisition, image processing, and mission control. The containers and release systems will be integrated with unmanned aerial vehicles (UAVs) and autonomous surface vehicles (ASVs), enabling air and surface oil spill combat capabilities. A dedicated software integrated into the vehicle control unit will control the release system. Furthermore, a customized multi-robot processing framework, depicted in Figure 3, will facilitate mission planning and control and the acquisition and processing of environmental data, providing valuable insights on oil spill combat throughout the mission. During the oil spill combat, each autonomous vehicle will have distinct roles: the UAV will be responsible for oil spill detection and aerial release of microbial consortia in areas inaccessible to the ASV. At the same time, the ASV will handle oil spill detection and validation and release the microbial consortia in border areas to contain the oil spill spread. The proposed approach requires the specification, development, and implementation of the two main blocks: hardware, containers, and release systems for bacteria and nutrients, able to be integrated into the autonomous vehicles (detail in Section 3); and a multi-robot framework for mission control, data acquisition, and processing.

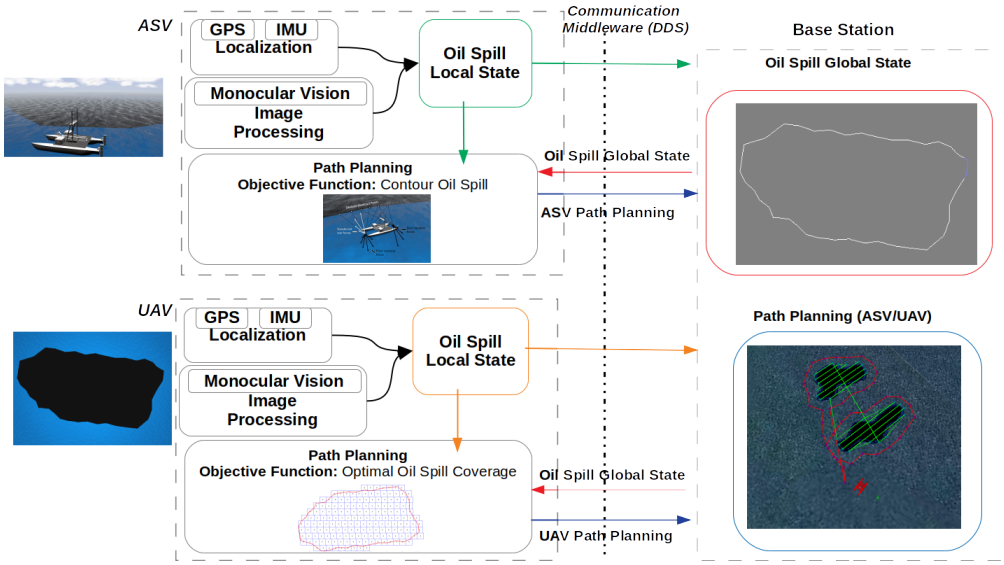

Figure 3. Multi-robot framework for oil spill mitigation.

The vehicle's estimated pose is provided by a localization block composed of an Inertial Measurement Unit (IMU) and a Global Navigation Satellite Systems (GNSS) receiver that are being fused by an Extended Kalman Filter (EKF). The monocular vision block provides the oil spill detection, where the image of the scenery will be acquired and processed (as described in [21]) to obtain clusters of oil spill spots. This block needs to output multiple points (in the image reference frame) representing the contour of the oil spill areas detected. Using the information provided by these two blocks, it is possible to obtain the georeferenced points of the contour. These points are then provided to the Oil Spill Local State block. The path planning block then uses this previous data, described in Section 2.1 (for the ASV) and Section 2.2 (for the UAV), where the control actions are generated to control the vehicle's movement along with the mission, to combat the spread of the oil slick. A data distribution service (DDS) communication middleware is also implemented, which is used to share the information of each robot to all network agents. The DDS protocol is based on a publish-subscribe paradigm with a data-centric approach, where the

Global Data Space identifies the data circulating within the system. A stable and reliable communication medium is achieved, given that DDS can control and optimize the use of resources, such as network bandwidth, CPU memory, and time. Therefore, each vehicle will provide the following information: acquired image (visible and thermographic cameras), position and attitude, estimated oil spill position, path planning, and vehicle status (battery status, tank level of lyophilized powder).

2.1. ASV Oil Spill Combat-Based Artificial Potential Field and Normal Vectors

The ASV mission will require navigating the stroke border areas of the oil spill. Therefore, the path planning method explored focused on having a cost function capable of covering all areas while avoiding oil spills. The algorithm developed for the ASV trajectory computation [21] is an adaptation from the standard Potential Field algorithm [22]. The ASV is a nonholonomic vehicle because it is equipped with two independent thrusters, making it impossible to perform sideways movement, which will require distinct attractive and repulsive forces to be applied to the front and rear bodies of the vehicle. These repulsive forces, represented in Figure 4, are computed by the distance between obstacle points and the vehicle's body, the sum of those repulsive and attractive forces constitute the resultant force, represented in Figure 4, that determines the motion of the vehicle.

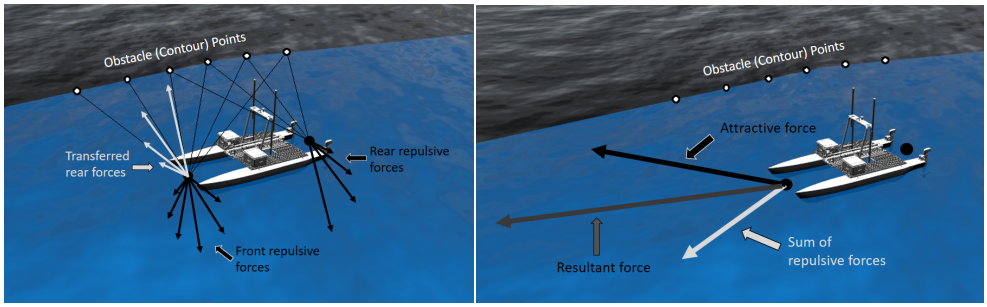

Figure 4. (**Left**): repulsive forces applied to the ASV for oil spill avoidance. (**Right**): resultant force from repulsive and attractive forces.

Considering an oil spill environment, the standard Potential Field algorithm cannot be applied, since there is no real goal defined, and the objective is not simply to avoid getting too close to obstacles but to follow the contour boundaries of the obstacles that describe the oil spill while maintaining a safe distance from it. Therefore, a new algorithm based on a new curvature-based approach was created, denominated by Normal Vectors Control Points + Artificial Potential Field (APF). This algorithm is responsible for computing a newly enlarged contour, resorting to normal vectors at points from the original contour. These new control points from the enlarged contour are put through the standard potential field algorithm as goals. This ensures the vehicle moves through all the points while maintaining a safe distance from the original contour (representing the oil spill).

The algorithm starts by taking three consecutive points from the contour, N − 1(x_{N-1}, y_{N-1}), N(x_N, y_N), and N + 1(x_{N+1}, y_{N+1}), and computing the Euclidean distance $d(N-1, N+1)$ between N − 1 and N + 1; Equation (1).

$$d(N-1, N+1) = \sqrt{(x_{N-1} - x_{N+1})^2 + (y_{N-1} - y_{N+1})^2} \quad (1)$$

The variables D_x and D_y are obtained by simply taking the differences of the positions in x and y, respectively, and dividing them by the Euclidean distance calculated previously, as represented in Equations (2) and (3).

$$D_x = \frac{(x_{N-1} - x_{N+1})}{d(N-1, N+1)} \quad (2)$$

$$D_y = \frac{(y_{N-1} - y_{N+1})}{d(N-1, N+1)} \tag{3}$$

Now, with D_x and D_y computed, it is relatively easy to obtain a new point (x, y), distanced κ from N(x_N, y_N), as represented in Equations (4) and (5). The parameter κ can be configured before the mission, and represents the repulsive energy between the ASV and the oil spill.

$$x = x_N + \kappa \times D_y \tag{4}$$

$$y = y_N - \kappa \times D_x \tag{5}$$

By repeating this procedure through every successive combination of three points in the contour ($N-1$, N, and $N+1$), a new set of points is obtained, distanced from the original contour points, that describe a new, enlarged contour, representing then, the intended ASV trajectory.

These equations describe the simple procedure of taking three consecutive points from the original contour, $N-1$, N, and $N+1$ (gray points in Figure 5) to compute the line segment that passes through $N-1$ and $N+1$ (represented in black). Next, the normal vector to that line segment at N is obtained, represented in red in the figure. The last step is to compute a new point, represented in green, on that normal, distanced κ from the original point N.

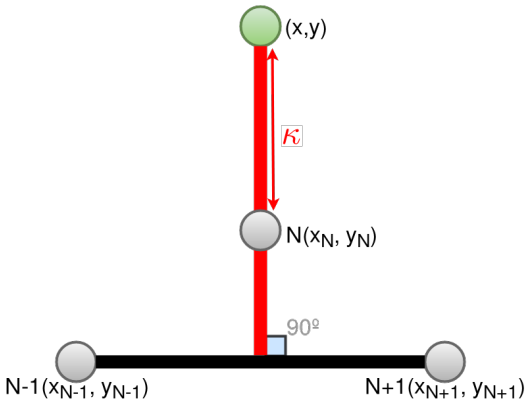

Figure 5. New point based on three consecutive contour points.

2.2. UAV Oil Spill Combat with Optimal Coverage

The oil spill mitigation maneuver proposed for the UAV is based on an Axis-parallel "zig-zag" algorithm [20]. This maneuver achieves complete coverage of the spill surface while deploying microorganisms and nutrients (bioremediation) capable of mitigating and containing the spillage. To compute the UAV path planning, we need to know the optimal maneuver height for the UAV that imposes the distance between the spreader nozzle and the surface, as well as the angle of dispersion of the powder spreader nozzle. Assuming that the dispersion of the nozzle forms the cone depicted in Figure 6, its action area on the water surface can be estimated as the largest square to fit in the cone base, represented in blue in the figure. The length of the defined square, L, can be obtained if the maneuver height for the UAV, H, and the angle of dispersion of the powder spreader nozzle, θ, are known. If the height of UAV, H, and the angle of dispersion of the powder spreader nozzle, θ, are known, the length of the defined square, L, can be obtained. For that, the diagonal of the cone base, D, is computed, with Equations (6) and (7), resulting in the computation of the action square length.

$$D = 2 \times (H \times \tan\theta) \tag{6}$$

$$D^2 = L^2 + L^2 \Leftrightarrow L = \sqrt{(D^2)/2} \tag{7}$$

With the dimensions of the action area estimated, the UAV's trajectory can now be computed. The goal is to ensure that the trajectory achieves the complete coverage of the oil spill surface, distributing lyophilized powder over its entire surface. The trajectories,

represented by the red lines in Figure 7, are obtained by the UAV path planning algorithm by dividing the points that define the spill into several horizontal layers, represented in the same figure in green, with the corresponding width from the action area square.

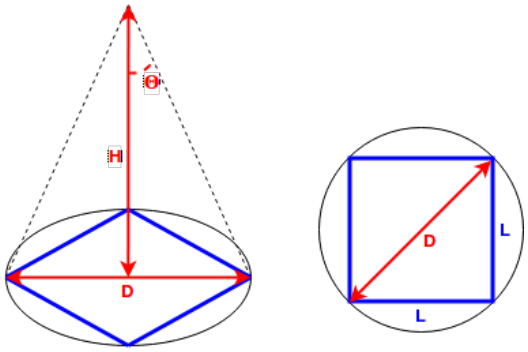

Figure 6. Coverage area of the powder spreader nozzle.

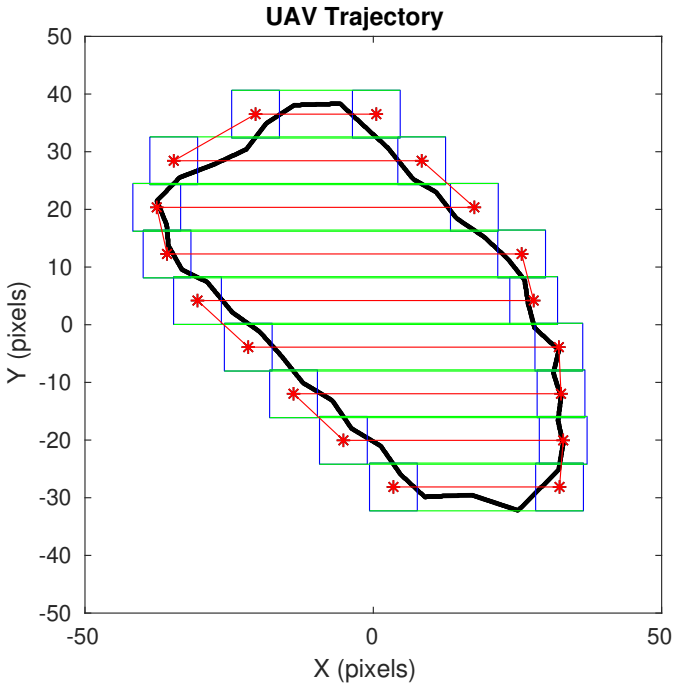

Figure 7. UAV path planning with the proposed algorithm.

The red markers (*) in Figure 7 represent the UAV waypoints corresponding to the minimum and maximum contour points along the X-axis in each previously obtained horizontal layer. This ensures minimal overlap and, consequently, minimal waste of resources while achieving complete oil spill coverage.

3. Autonomous Vehicles for Oil Spill Mitigation

The oil spill mitigation will be performed with a team of heterogeneous autonomous vehicles, an ASV and a UAV, that will cooperatively ensure a fast and optimal intervention. Therefore, two autonomous vehicles (STORK I [23] and ROAZ II [24]) have been adapted to support the proposed microbial release system. A new one, GRIFO-X, has been developed with features that allow for the intervention of more robustness to the weather conditions, like wind, and also with a payload improvement to transport and spread more quantity of lyophilized powder.

3.1. Autonomous Surface Vehicle

The ROAZ II [24], depicted in Figure 8, is an autonomous surface vehicle (ASV) designed for maritime operations. It is a 4.4 × 2.2 m robotic catamaran equipped with a wide range of navigation and maritime monitoring sensors, like radar, to detect other vessels [25]. It can perform predefined maneuvers or adapt its behavior due to external events. If the ASV ROAZ is on a collision course with another ship during the mission, the ASV generates an alert to the ground station and requests authorization to initiate the avoidance maneuver based on the information available on the radar [25]. In the oil spill scenario, ROAZ is equipped with a system that allows it to pump water from the ocean, mix it with the bioremediation microorganism powder, and spread it over the oil plume (see Figure 8).

Figure 8. ASV ROAZ II adapted for oil spill mitigation.

3.2. Unmanned Aerial Vehicles

The UAV will have the mission of detecting the oil spill and also the ability to spread the lyophilized powder over the oil spill. Therefore, two multi-robot UAVs have been developed. Table 1 summarizes the main features of each UAV.

Table 1. UAVs feature descriptions.

Features	STORK I	GRIFO-X
Size open (D × H)	1060 × 570 mm	1522 × 1590 mm
Size close (D × H)	670 × 570 mm	858 × 998 mm
Motors	6 × DJI E2000 Pro	6 × DJI E5000 Pro
Weight (with batteries)	9.3 kg	25 kg
Batteries	22.2 V–22,000 mAh	6 × 22.2 V–22,000 mAh
Flight time	20–25 min	40–45 min
Release System Capacity	1 kg	15 kg
	Navigation	
GNSS	Ublox NEO-M8T e ComNav K501G	Unicore UB482 dual antenna
Autopilot	INESC TEC autopilot	INESC TEC autopilot
IMU	STIM300	STIM300
	Perception	
Cameras	Pointgrey Grasshopper3	Teledyne Dalsa Genie Nano GiE
IR Camera	Teledyne Dalsa Calibir DXM640	Teledyne Dalsa Calibir DXM640
LiDAR	Velodyne VLP-16 *	Velodyne VLP-16 *
CPU	Odroid XU3	i7-6822EQ with 16 GB of RAM DDR4

* Mounted only for 3D reconstruction missions [26].

The UAV STORK I was already available for field tests in applications such as search and rescue operations, environmental monitoring, 3D mapping, inspection, surveillance, and patrol. It consists of a customized heptagon geometry integrating six rotors on the back and a pan and tilt gimbal on the front side with 120° of field-of-view. The gimbal sensor payload comprises two cameras, a thermographic camera and a high-resolution visual camera. The UAV was designed to be modular and integrate new sensors, such as a LiDAR

system for 3D reconstruction, obstacle detection, and avoidance [27], and a hyperspectral camera [28]. The system relies on a high-accuracy navigation system with a custom-made autopilot, Real-Time Kinematic GNSS centimeter-level precision, and a high-accuracy IMU, making it a versatile platform capable of integrating various application scenarios, such as mitigating oil spills. It provides a total takeoff payload capacity of 15 kg with an endurance of 25 min, and is prepared to carry 1.5 kg of bioremediation powder.

Generally, oil spills affect a large area of the sea, requiring more powder payload to increase bioremediation efficiency on each mission and being more robust to adverse weather conditions like strong winds. Therefore, a new UAV frame was developed, denoted by GRIFO-X (previously known as STORK II), Figure 9. It is also a carbon fiber hexacopter platform with a novel design and an overall payload of 50 kg. Based on the previous generation, the vehicle provides a 90° frontal field-of-view for vision perception (thermographic and high-resolution visual cameras), a landing damper system to support the payload, and an adjustable sliding battery system for fine-tuning the center of mass (Figure 9). It provides an endurance of 40 min, and was validated with 14 kg of bioremediation powder.

Figure 9. UAV STORK I (**left**) and GRIFO-X (**right**) prepared for oil spill mitigation missions.

3.3. Autonomous Vehicles Remarks

In a comparative analysis of both UAVs adapted to combat oil spills, the greatest contribution of GRIFO-X in comparison with STORK I is related to the bioremediation load capacity and flight time, which will allow greater efficiency in the combat process. Compared with other UAV approaches, the fixed-wing ScanEagle and the PITVANT UAVs [16] can detect oil spills but do not have combat capabilities. The proposed solution is disruptive and innovative, allowing real-time detection of oil spills and a rapid response because the UAVs are equipped with microorganisms capable of starting the mitigation process and quickly containing the oil spill spread. Concerning the ROAZ ASV, we are in the presence of a robotics solution with the capacity to contribute in two fundamental axes of the oil spill combat: (1) the ability to be used as a rapid deployment vehicle in the incident area, allowing spill containment without the use of heavy machinery [5]; and (2) being used as a UAV landing and recharge platform (ongoing development). It is also important to highlight that both proposed autonomous vehicles were evaluated in terms of their operational limits in terms of maximum wind speed, wave height, and wave period, taking into account their intervention on the coast of Portugal and Spain [29].

4. Release Systems

Considering each vehicle's payload constraints and operation conditions, the release system must be developed and adapted for each platform.

For aerial vehicles, the idea is to develop a suitable system that can be integrated with unmanned and manned vehicles and execute missions autonomously. To maximize the bioremediation substance's density and increase the efficiency of the aerial missions, the release system uses lyophilized consortia instead of a mixture of bacteria and water.

Based on these requirements, the system must have a versatile control system composed of an embedded microcontroller able to support several communication protocols

(CAN, RS232, and RS485), a tank for the lyophilized powder, a valve, and a motor driver to control the quantity of bacteria mixed on the airflow, and an optional GNSS and IMU system, for the autonomous preloaded tasks (Figure 10).

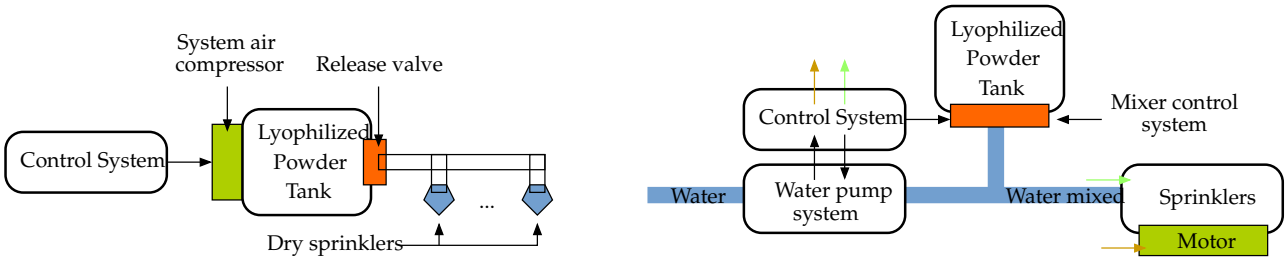

Figure 10. Release system conceptual architecture for both autonomous vehicles. (**Left**): UAV release system for lyophilized spread. (**Right**): ASV release system with the ability to mix lyophilized powder mixture with native water.

The first UAV release system developed was based on STORK I features. This prototype consists of a vertical cylinder tank for 1 kg of lyophilized bacteria, a regulation valve actuated by a servo motor, a turbine that generates airflow in the tank, and a nozzle to spread the bacteria. The functionality of the system relies on the vacuum forces inside the reservoir. By actuating the turbine and opening the valve, the airflows create suction on the tank, blowing the powder through the nozzle and releasing the bacteria into the oil spill, as depicted in Figure 11.

Figure 11. UAV release system developed for both UAVs. (**Left**): release system for UAV STORK I with a capacity of 1 kg. (**Right**): release system for UAV GRIFO-X with a capacity of 7 kg on each reservoir, with an overall capacity of 14 kg.

A second version was developed with a maximum of 7 kg of lyophilized bacteria to increase the release system's capacity. This system can be integrated into pairs to the GRIFO-X, presenting an overall of 14 kg of consortia (Figure 11).

The developed ASV release system (Figure 10) comprises a water pump that is responsible for suctioning water and creating a powerful flow and a micro-pump that injects a bacteria concentrate into the same flow. Attached to the sprinkler, a motor is responsible for throwing the mixed water flow to the oil spill in the correct orientation. Figure 12 shows the water pump, micro-pump, and other components mounted in a water-proof box.

Figure 12. ASV release system. Water pump and control system box.

The release system assembled in ASV ROAZ is detailed in Figure 12, with the white hose that connects the water pump to the sprinkler. During the field tests, even with the wind, the system released a mixed solution with a median distance of 12 m from ROAZ, the expected distance defined in the initial requirements.

5. Oil Spill Simulation Environment

A critical step in developing a strategy for oil spill mitigation is evaluating the cooperative behavior between both heterogeneous vehicles in the presence of an oil spill. Therefore, a simulation environment was developed with the following requirements: (1) provide a realistic 3D environment able to simulate the water buoyancy effect, the effect of the sun in the water, and the oil spill; (2) direct integration with the perception layer onboard on each vehicle, allowing in the future to switch between simulated cameras with real cameras (visual and thermographic cameras); and (3) straightforward integration with the vehicle's actions (waypoint) generated by the multi-robot path planning framework layer (see Figure 2).

Based on these requirements, the chosen simulator was the 3D simulator Gazebo [30]. Gazebo is an open-source project developed by the robotic community for various applications. It is fully integrated with the framework ROS [31]. It provides an extensive library of common sensors used in robotics, such as cameras, GPS, and IMU, and provides the water waves and buoyancy effect.

The simulated oil spill environment is composed of the following items: the autonomous vehicles, the ASV ROAZ II and the UAV STORK I, both of them imported from the mechanical design; a realistic ocean environment representation from [32]; and an oil spill darker color mesh created on top of the previously existent ocean mesh. The overall results are detailed in Figure 13. The developed environment was also used during the field tests to provide the oil spill image to both autonomous vehicles, as depicted in Figure 17.

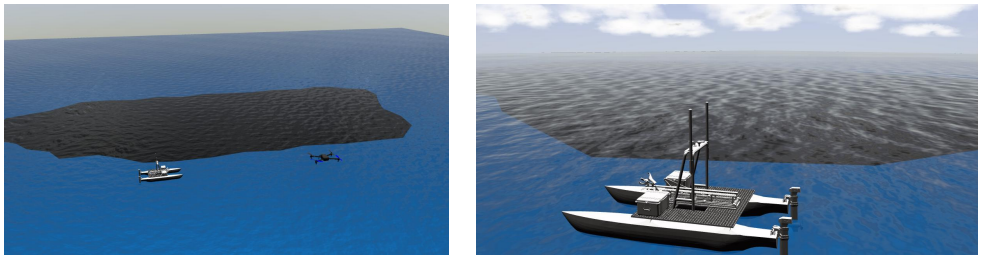

Figure 13. Oil spill simulation environment developed in Gazebo to provide the oil spill to both vehicles during the field tests.

6. Field Tests

The field tests were performed in different scenarios and places. To enumerate them: harbor of Leixões, Medas, and Lisbon Naval Base in Alfeite—Portugal, and also in the harbor of Coruña Spain (see Figures 14 and 15). To provide a quasi-real-world disaster,

the field tests were carried out with a combination of an oil spill in a simulation environment in a real-world localization (see Figure 17).

Figure 14. Field tests during the robotics exercise (REX).

Figure 15. Field Tests in Puerto of Medas, Portugal and Coruña, Spain.

The existence of a link between the physical world and the simulation scenario allowed the UAV and ASV robots to localize the oil spill autonomously, path-planning the vehicle trajectory, and perform the mitigation maneuver.

The ASV mission consists of a maneuver to surround the oil spill and use the sprinkler to spread the mixed water into the oil spill. The UAV mission consists of an efficient Axis-parallel "zig-zag" maneuver, where the lyophilized bacteria consortia are spread across the oil spill, as detailed in the algorithm in Section 2.2.

The preliminary tests occurred in the Leixões Harbor in Porto, Portugal, with a single simulated oil spill placed close to shore. The UAV computed trajectory was formed by 18 waypoints covering the oil spill, while nine waypoints formed the ASV trajectory. This low number of waypoints represented the ASV maneuver due to the minimal distance of 30 m between each waypoint. The reduced turning angle of this specific surface vehicle imposed this condition. A slight drift occurred from the intended trajectory due to harsh weather conditions, strong wind, and water currents. The vehicle trajectory concerning the simulated oil spill is present in Figure 16.

A second field test was performed in the Medas Douro River in Porto, Portugal. Two simulated oil spills were placed in the river's middle to increase difficulty. The ASV mission planner generated 36 waypoints to cover the two zones, and the UAV mission had 20 waypoints corresponding only to one zone. Figure 15 in the left shows both vehicles performing the cooperative autonomous mitigation task in the real scenario.

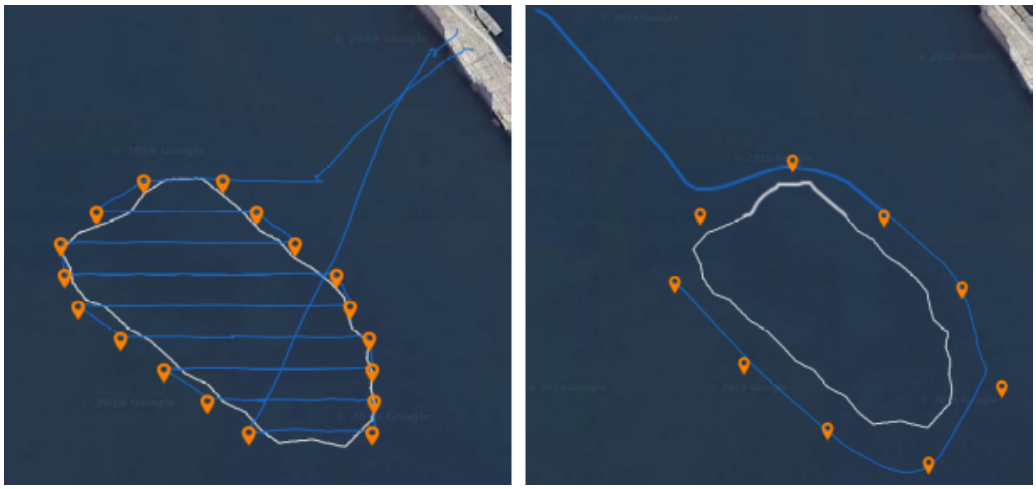

Figure 16. Trajectory behavior of both vehicles to mitigate the oil spill. Field test in the harbor of Leixões, Portugal.

Figures 15 and 18 show the vehicles performing the cooperative autonomous mitigation task in the Puerto de A Coruña.

The final tests occurred in Puerto de A Coruña, Spain, where two simulated oil spills were placed close to shore, as shown by Figure 17. Figure 18 shows the results obtained by this mitigation mission. The waypoints were generated and sent to the vehicles (39 waypoints for the ASV and 26 waypoints for the UAV), as represented by the orange markers, the white lines are the detected oil spills, and the blue lines represent the real trajectory of the vehicles. As depicted in Figure 18, both autonomous vehicles carried out the mission successfully. In the particular case of the ASV, the oil spill contour mission takes approximately 15 min, covering a total distance of 1270 m, and is carried out at an average speed of 1.5 m/s, and a safety distance of 2.5 m related to the oil spill. In the case of the UAV, the intervention was inside the oil spill to ensure total coverage. The mission from takeoff to landing lasted 18 min, with a total distance covered of 2600 m, a safety distance of 3 m from the water, and an average operating speed of 3 m/s. Both vehicles started the mission from the harbor of Coruña. However, the algorithm executed in each autonomous vehicle is prepared to generate the maneuver from the moment they have information about the simulated oil spill and the estimated position.

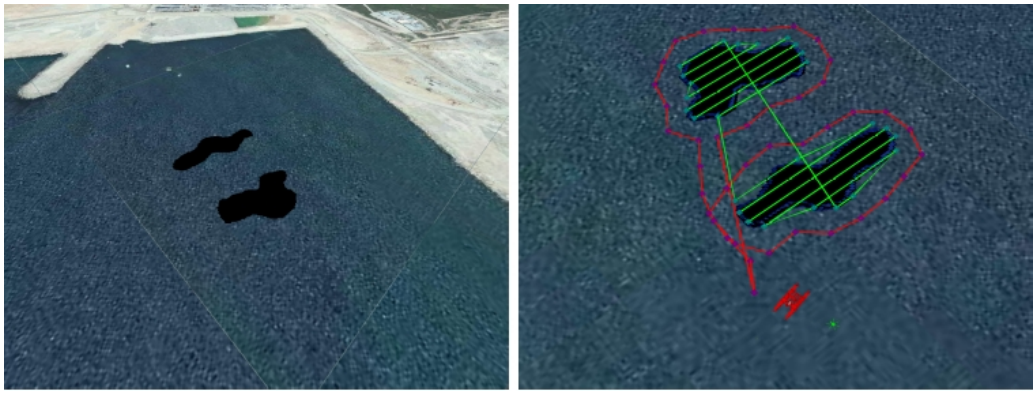

Figure 17. (**Left**): simulated oil spills in the Puerto A Coruña. (**Right**): ground Station 3D graphical user interface for monitoring the mission with the position of both vehicles and the generated path planning.

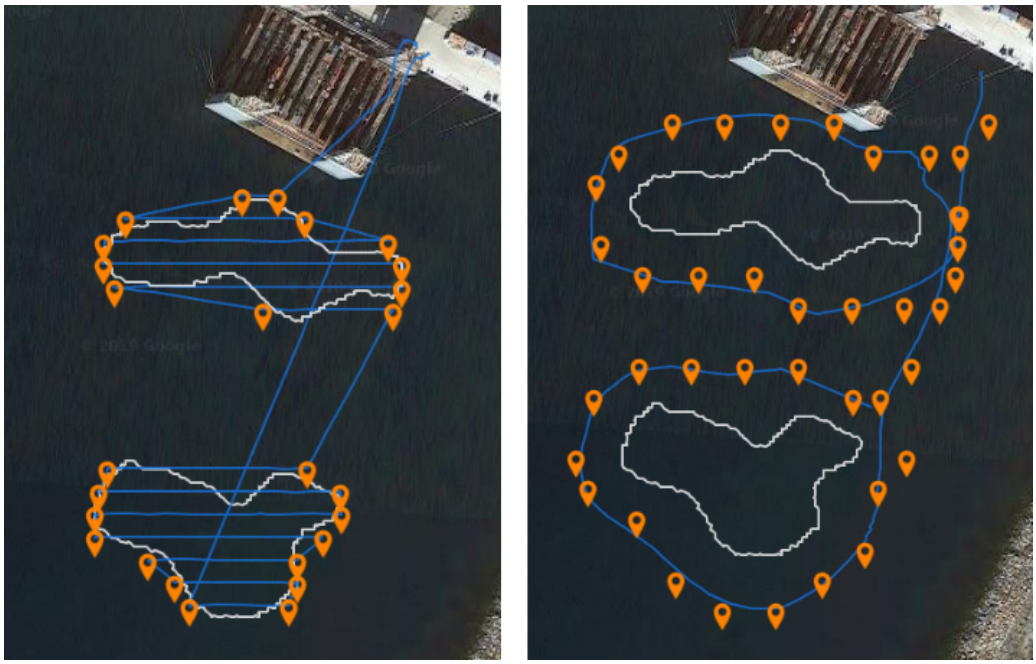

Figure 18. Trajectory behavior of both vehicles to mitigate the oil spill. Field test in the harbor of Coruña, Spain. (**Left**): UAV trajectory over the oil spill. (**Right**): ASV trajectory contours the oil spill.

During the field tests, both vehicles were able to perform the mission, even when we moved the oil spill position, with the perception layer being able to detect a new oil spill and share the information with the vehicle's path planning layer. A critical improvement to the field tests is having a more coordinated task between the ASV and UAV to ensure that both vehicles are not covering the same oil spill area. We experienced one situation where the UAV spread the powder inside the range of the ASV water pump sprinkler, which means that the ASV spread water can damage the UAV.

A real-time application for 3D visualization and monitoring the ground station's mission was developed in RVIZ–ROS, as depicted in Figure 17. The oil spill included in the scenario is represented by the black areas, where the blue squares draw the detected contours. The red lines and the squares show the path planning and waypoints for the ASV ROAZ (red vehicle), and the green lines and squares are the path planning and waypoints of UAV STORK (green vehicle near ROAZ).

The field test videos are available in the supplementary movie [33].

7. Conclusions and Future Work

The paper presents a novel approach for oil spill mitigation with a team of heterogeneous autonomous vehicles based on native microbial consortia with bioremediation capacity. The proposed approach allows us to have a first-line response that is more cost-effective without risking human lives. The algorithms for optimal intervention are present, and the release systems are developed for the UAVs and the ASVs.

The work was part of two research projects, the Portuguese National project ROSM—Robotic Oil Spill Mitigation, and the European Project Spilless—First-line Response to Oil Spills based on native microorganism cooperation.

At the end of the projects, there are lines of work that have emerged and will be addressed as future work: (1) integration in the UAV of a radar-based altimeter to ensure that we can spread the powder near the water, with more robustness to the wind effects; (2) carrying out the development of a gyro-stabilized landing pad in the ASV to allow UAV takeoff and landing. This approach will also allow the development of a system able to perform UAV battery and lyophilized powder recharge available in the ASV; (3) extending the multi-robot proposed framework to support more than one UAV during the oil spill intervention, creating sub-areas of intervention/coverage based on the available lyophilized

powder payload; (4) integrating a sensor into the UAV release system to measure the amount of bioremediation released over the oil spill; and (5) the simulation environment does not consider the effects that could infer dynamics in the oil spread. Therefore, we would like to improve the oil spill simulation by adding to the oil spill spread effect considering the wind and the water current, as proposed in [34].

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

APF	Artificial Potential Field
ASV	Autonomous Surface Vehicle
AUV	Autonomous Underwater Vehicle
DDS	Data Distribution Service
EKF	Extended Kalman Filter
GA	Genetic Algorithm
GNSS	Global Navigation Satellite Systems
IMU	Inertial Measurement Unit
LiDAR	Light Detection and Ranging
ROS	Robot Operating System
ROV	Remotely Operated Vehicle
UAV	Unmanned Aerial Vehicle

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