Development of an Unmanned Capsule for Large-Scale Maritime Search and Rescue

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Abstract *– This paper describes the development and testing of a robotic capsule for search and rescue operations at sea. This capsule is able to operate autonomously or remotely controlled, is transported and deployed by a larger USV into a determined disaster area and is used to carry a life raft and inflate it close to survivors in large-scale maritime disasters. The ultimate goal of this development is to endow search and rescue teams with tools that extend their operational capability in scenarios with adverse atmospheric or maritime conditions.*

I. INTRODUCTION

Deaths associated with maritime accidents occurred during fishing, recreational or sports activities are still a major social concern. Due to this problem, many search and rescue teams are trained in order to act swiftly and in a feasible way, aiming to reduce the risk of death associated with such accidents.

It is important to highlight that during maritime search and rescue operations, the safety of the rescuers is a major issue and must be ensured in any circumstance. Therefore, these teams are often forced to adapt, or even to suspend their operations due to external factors and conditions, such as lack of visibility or atmospheric and/or maritime adverse conditions. It should be pointed out that rescue response time is a major factor for success in these operations due to the reduced survival time of victims that fall overboard.

Robotic assets can therefore complement the role of search and rescue teams, as they can operate in dangerous scenarios and under adverse environmental conditions without putting human lives in danger. This is the fundamental idea behind ICARUS (Integrated Components for Assisted Rescue and Unmanned Search Operations) – a FP7 Project lead by the Belgium Royal Military Academy [1]. This project aims to develop robotic tools for search and rescue operations, both in urban and maritime scenarios, with a particular focus on large–scale disasters. These scenarios are characterized by the mismatch between the size of the disaster and the dimension of the existing search and rescue response.

II. ICARUS PROJECT AND MARITIME SEARCH AND RESCUE (MSAR) OPERATIONS

As part of the ICARUS project, particularly in the maritime scenario, multiple heterogeneous unmanned platforms (by air or surface) will cooperate, in order to detect and assist castaways. This assistance may include providing means for the floatation and thermal protection, preventing from fatigue, drowning or hypothermia, thereby increasing the survival rate. Furthermore, when the conditions do not permit the manned SAR operations, a fast and effective operation within the disaster scenario by the robotic assets, makes it possible for the rescuers to evaluate and remotely assist the castaways before resuming action as soon as the safety conditions are ensured.

This paper describes one of the components of the ICARUS tools for the maritime scenario – a robotized capsule able to move (autonomously or remotely operated) towards survivors, while carrying an inflatable life raft.

Projects such AGAPAS (Autonomous Galileo-Supported Rescue Vessel for Persons Overboard) and EMILY (EMergency Integrated Lifesaving lanYard) are projects that aim as well to develop robotic assets for maritime search and rescue. The AGAPAS is a project orientated specifically to person overboard situations, where an automatic system perceives that someone fell from the vessel and deploys a USV capable of fetching that person [2]. The EMILY is a remotely operated/ autonomous vessel that aims to assist the life guards in crowded beaches, providing them a safe and fast response mean [3].

III. SYSTEMS OPERATION AND COORDINATION DURING LARGE-SCALE MARITIME DISASTERS

In the scope of the ICARUS project two different segments of unmanned platforms are planned, one aerial segment responsible for detection and tracking of castaways in the disaster area, and a maritime segment that will directly interact with the victims.

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The aerial segment is composed by UAVs of two types: fixed-wing and rotorcraft. They will perform the sweep of the areas where victims are probable to be located, and will track the located victims providing updated information to the maritime segment. Those locations will be treated by the maritime segment in order to be translated into waypoints and deployment spots.

The maritime segment is composed by two different types of USVs. A larger USV that will carry on board a few smaller USVs, called the Unmanned Capsules (UCAPs). The larger USV has the capability of navigating for large distances and will carry the UCAPs to be separately deployed in the disaster zone. The UCAPs are the platforms responsible for directly assisting the castaways providing them means for floatation and thermal protection. These means consist of life rafts carried on board of the UCAPs, deployed and inflated automatically close to the victims.

IV. UNMANNED CAPSULE (UCAP)

The requirements for the Unmanned Capsule Platform are part of the outputs of a study accomplished in the scope of the ICARUS Project, together with end-users that work in maritime search and rescue. According to these requirements the Unmanned Capsule has to be transported and deployed from a larger USV and designed to carry and deploy a standard 4 person life raft with a maximum weight of 30kg. Some other relevant requirements are that the prototype range should be at least 0.6 nautical miles, capable of navigating under sea state 3 (wave height up to 1.25m – Douglas Sea Scale) and wind conditions 6 (wind speed 22 to 27Knots - Beaufort), and the UCAP should be able as well to navigate at a minimum speed of 2 knots.

For the first prototype, see Fig. 1, the design of the hull was based on the displacement hull of a small sailboat with a few adaptations in order to fit the dimensions and the weight versus floatation requirements. The hull is made of fiberglass and is covered with a wooden deck. On deck, two hatches allow access to the interior of the vehicle, where batteries and electronics are installed, and two sealed faceplates provide room for electrical interfaces to the outside. Currently, two cable glands are installed, one for the cable of the life raft deployment system and the other for the antenna cable. The antenna is located at the tip of a small mast, in the aft section.

The UCAP weight is 30kg and the life raft used is about 25 kg. The total floatation of the UCAP is 90 kg so it navigates with approximately two thirds or one third of the hull submersed when with or without the life raft on board, respectively.

The used life raft is a Eurovinil 4P Standard International, which is a commercial 4 person model measuring 680x380x250 millimeters before inflation. The life raft consists of two independent inflatable buoyancy tubes, provided with a single floor and an inflatable arch tube supporting the canopy. The material of the hull of the life raft is E.M.C (Eurovinil Marine Compound). The inflation system is based on a VTE 99 multidirectional firing mechanism. Finally, the life raft carries on board aid equipment such as drinking water and provisions, a first aid kit and signaling equipment.

Fig. 1 - Unmanned Capsule Prototype

A. Hardware and Sensors

Aboard the UCAP are installed two 12V14Ah lead-acid batteries, yielding a total energy of 336Wh. The total weight of the batteries is 9.5kg, and they are installed in the bottom of the hull to lower the center of mass and increase roll stability.

The on board computational system is a PC104 stack composed by a 500 MHz CPU board (Pegasus PGS800-256-2G) and a power converter board (Tri-M Engineering HE104-DXL). This system communicates with the operations console via Wi-Fi, using a WRT54 router from Linksys connected to an L-Com 7dB antenna.

The navigation system is based on a PNI Trax AHRS module as an Inertial Measurement Unit and a u-blox NEO 6T GPS.

The propulsion system is composed by two Seabotix BTD150 thrusters for differential drive motion, and by the motor controller board, a Roboteq AX500 board. Each of these thrusters is capable of a continuous thrust of 2.2 kgf, and peaks of 2.9 kgf.

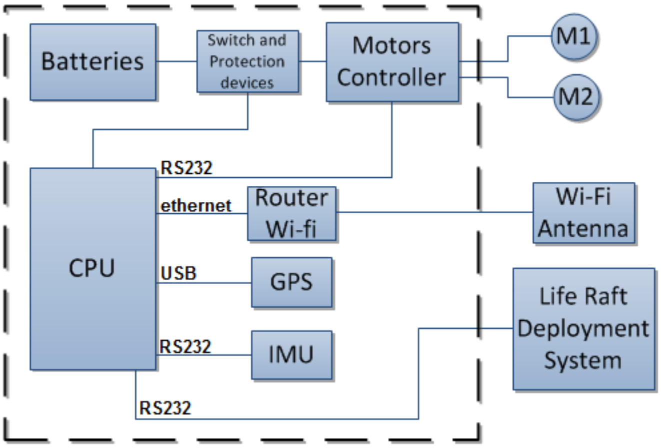

Fig. 2 - Unmanned capsule system architecture.

B. *Onboard Software*

The onboard software is composed of several modules that communicate with each other using a message passing mechanism. These modules follow a hierarchical architecture similar to the one use in other INESC TEC robotic systems [4] [5]. At the lowest level lie the modules that interact directly with the sensors and actuation devices, constituting a hardware abstraction layer. On top of these two major modules are responsible for the navigation (real time estimation of the UCAP position, velocity and attitude) and for the control (execution of maneuvers and other high level behaviors). A set of other specific modules implements supervision tasks, as well as communication interfaces with external systems, namely for command and control.

The navigation module processes data from the GPS and IMU systems. The GPS system provides the information about location and velocity. The IMU has incorporated magnetometers, accelerometers and gyroscopes providing information about yaw, pitch and roll states, acceleration and rotational movements decomposed in the three system axis. A data fusion algorithm is used to estimate the position of the capsule whenever the GPS receiver loses track, possibly due to excessive roll or pitch caused by stronger waves. At the same time, the inertial data is used to obtain updated information on the external disturbances, allowing to a better characterization of the navigation environment.

The control module is responsible for the definition in real time of an actuation commands for the two thrusters. Usually this is done by specifying the common mode (used to define speed) and the differential mode (used to define rotation). Different feedback loops can be established to allow the UCAP to carry out missions with different degrees of autonomy, performing different types of maneuvers in several different modes.

The different UCAP operating modes are: **1) Autonomous Mode** which consists of autonomous operation with a pre-programed mission described in a proper mission file. **2) External Mode** which consists of autonomous operation with remotely programed mission in real time. **3) Anchor Mode** that allows performing station keeping, where the USV will keep its position compensating drifts caused by winds, currents or other influences. **4) Remote Control Mode** where the UCAP can be remotely controlled by the user. **5) Idle Mode** where the UCAP actuation is shut down, causing it to drift according to external disturbances (winds and currents).

A UCAP mission is composed by a combination of several basic maneuvers that the UCAP is able to perform autonomously. These maneuvers are: navigation to a determined waypoint, path following, station keeping and waiting for an external condition or event.

In order to be able of executing such maneuvers, the UCAP has implemented routines that are based on PID controllers for speed and heading in a lower level and line or anchor controllers in an upper level. These controllers are responsible for defining the proper actuation for the thrusters so that the expected behavior is observed and the navigation offsets are compensated and minimized.

The speed controllers are responsible for defining the actuation for thrusters so that a determined navigation speed for the UCAP is observed. The heading controllers are responsible for adapting the differential actuation for thrusters so that the UCAP heads to the goal adjusting constantly its attitude.

With the mentioned low level controllers suited, it is possible to implement the higher level controllers that allow the UCAP to follow a defined path or to keep its global position under external influences such as wind, currents or others. So the line controllers are responsible for setting the proper heading and speed parameters according to the goal waypoint. The anchor controllers are used when the UCAP is doing station keeping and controls constantly the distance from the point and its relative orientation. Taking these parameters into account the controllers will set the proper heading and speed parameters so that the lower level controllers are able to set the proper thrusters actuations.

The supervising module is responsible to monitor a set of internal values, such as temperature, power consumption, or available energy, and send alert messages or trigger emergy behaviors whenever faults are detected. It also monitors the communication link to make sure that the UCAP is put into idle mode or returns to a safe place whenever this link is broken, and remote control of the UCAP is lost.

C. *UCAP Control and Supervision*

The user can interact with the UCAP through a graphical user interface running in an ordinary Laptop. It allows controlling the UCAP, supervising mission executions and monitoring its state data and on board parameters. A snapshot of this console is presented in Fig. 3.

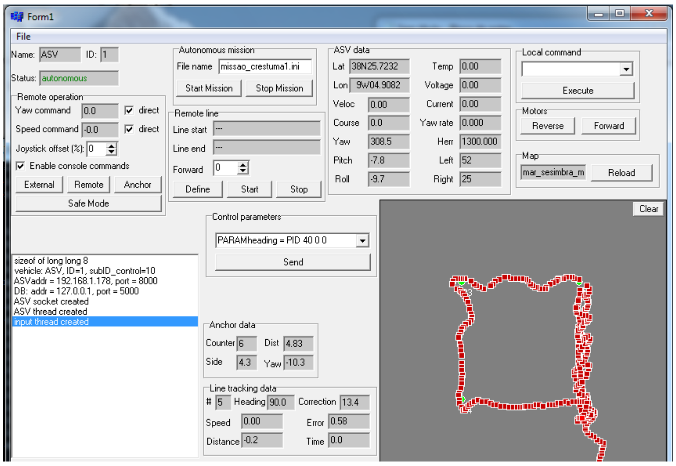

Fig. 3 – UCAP operations console

The operations console allows the user to set the different operating modes of the platform, to define mission parameters and attribute tasks to the platform, to refine control parameters used by the platform control routines, and to control directly the platform throw the usage of an ordinary joystick. Moreover, this console allows monitoring in real time all data concerning to the platform, such as the operating mode, the maneuver data such as distance to goal or off-track distance, sensors data such as position, attitude, speed, thruster's actuation, batteries status, temperature, voltage and current consumption.

Communication between the console and the UCAP is based in a standard Wi-FI link, using standard UDP messages. These messages convey commands from the console to the UCAP and telemetry or payload data from the UCAP to the console. Each message is composed by the header and the payload. The header contains the information about the origin/destination of the message and the type of exchanged data. Commands are sent directly to the destination, while telemetry and payload data are sent to a common repository that allows subscriptions from relevant clients. In this way it is possible to have different configurations for the command and control of the UCAP, either having for example a common command a control station for multiple UCAPs or a separate command and control for each capsule, with a possible common supervision console.

This protocol also allows for the use multiple communication links between the UCAP and the control station. This feature might be useful for scenarios where a long range, narrow bandwidth link might be used for remote operations.

D. Life Raft Deployment System

As soon as the UCAP is close enough to the castaways, the life raft is deployed and inflated autonomously. The electro-mechanical system developed to deploy the life raft is shown in Fig. 4 and Fig. 5:

Fig. 4 - Life Raft deployment system.

Fig. 5 - Life Raft deployment system with the Life Raft.

The life raft is transported on a mat of rollers and held in place by thin wires that act as mechanical fuses. To deploy it, there is a compressed spring inside a PVC pipe, connected to a life raft pusher by a line that passes through a pulley system, see Fig. 4.

The spring is similar to the ones that are used to hold the trunk of a car, see Fig. 6.

Fig. 6 - Spring decompressed.

This spring is initially compressed by an own made mechanism, shown in the following figure, Fig. 7.

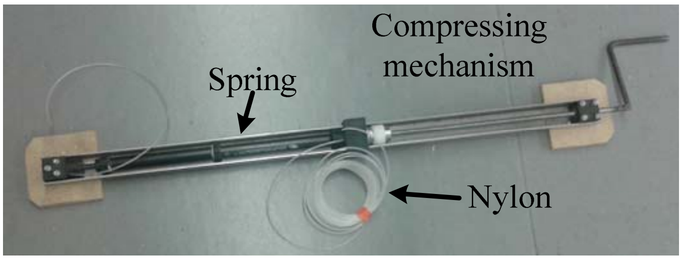

Fig. 7 - Compressing mechanism.

After being compressed, the spring is held in that position by a nylon cable, as shown in Fig. 8.

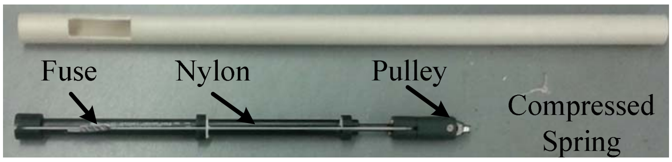

Fig. 8 - Spring on the compressed position.

When the system is fully assembled, the compressed spring is introduced inside the PVC pipe, which is fixed to the UCAP. The nylon cable that holds the spring is involved by an electrical wire, connected to the main computer. Upon a signal from the main computer, a current runs through this wire, melting the nylon cable and therefore starting the decompression movement. This extension of the spring acts on the pulley system, breaking the mechanical fuse that holds the life raft in position and deploying it into the water. At the same time, a tensioned cable fixed to the UCAP and in the life raft will act on the life raft's inflation system, causing its automatic inflation during deployment.

V. ROAZ

The ROAZ USV [6] was used as the deployment platform for the UCAP preliminary prototype tests.

ROAZ is a twin hull autonomous surface vehicle developed for oceanic robotics research and monitoring. It is based on a high density polyethylene 4.2m long catamaran capable of operating in ocean environment equipped with electric propulsion (two 2kW thrusters). With an autonomy of operation (depending on the battery configuration and speed) 8h to 10hr it can reach 10knots of maximum velocity.

A. Hardware and Sensors

The vehicle main control computer is mounted on a central watertight enclosure and the 8 50Ah LiFePo batteries are installed in two additional enclosures.

The vehicle main communications are achieved by an IEEE 802.11a link with the antenna mounted in an upper platform. This platform also houses the vehicle vision system, comprised of a pan & tilt infrared camera unit (ThermalEye 5000XP), a digital color camera (Bashler 1300ac GigE) and an analogue pan&tilt dome camera used only for streaming video purposes.

The vehicle navigation sensors are a precision L1/L2 RTK GPS (Septentrio PolaRx2) and an inertial motion unit (Microstrain 3DM).

Also mounted in the tower there is a low power broadband radar (Lowrance 3G) and the GPS antenna.

In a lowered underwater sensor unit, the USV has a sidescan sonar (Imagenex Sportscan), a multibeam sonar (Imagenex DeltaT) and a single beam echosounder (Tritech digital altimeter).

B. Navigation and Localisation

Due to the high precision (in the order of a few cm with RTK), availability in the marine environment and update rate (10 Hz) of the GPS system, this is the main localization sensor.

The relatively low quality of the inertial unit leads to its use for attitude determination and in particular for heading information (when GPS course is not available).

When required, a loosely coupled EKF filter is used to improve the overall localization quality (mainly for correcting the yaw angle estimation).

The GPS system can be used either in a standalone configuration or with RTK corrections when available. In addition it can have multiple antennas and thus also provide heading information for the localization filter.

The vehicle autonomous control is capable of executing waypoint or trajectory defined missions (such as “lawnmow” area coverage) or sensor based maneuvers (for ex: vision based control).

In addition, the vehicle can also be directly supervised from a remote console or teleoperated.

C. UCAP Deployment System

In order to deploy the UCAP from ROAZ USV, a deployment system, consisting of a mechanical structure and a trigger mechanism, was developed and assembled aboard of ROAZ.

The test structure consists of a ramp that allows the gravity to be the main force imposing forward movement to the UCAP during launch and a trigger mechanism that is responsible for releasing the Capsule in the appropriate moment. On it's ready to launch position the Capsule sits on rubber rollers that ease the movement in the forward direction and constraint it in the transversal direction.

In future developments the USV should accommodate two to four capsules to be released sequentially.

The trigger mechanism receives its commands trough a CAN bus. This type of bus is well tested in the automotive industry, is robust to electromagnetic noise and has a maximum 1MBit/s data bandwidth.

Fig. 9 - UCAP Deployment system installed in ROAZ USV

VI. Experiments

The experimental tests consisted of three days of exercises with the Portuguese Navy in Lisbon, Portugal, and five days of exercises in the scope of the ICARUS Project in La Spezia, Italy, on coastal sea waters. The aims of the exercises were to test, refine and demonstrate the deployments of the Unmanned Capsule from the larger USV, the UCAP navigation capability while carrying out autonomous missions and deploying the onboard life raft.

A. Exercises With The Portuguese Navy in Lisbon/Portugal

These first tests occurred between July 3rd and 5th, in the Atlantic Ocean coastal waters off Sesimbra, Portugal. The testes occurred with the support of the Portuguese Navy and particularly the Portuguese Naval Research Centre (CINAV). The experiments were made aboard a military ship, about 2 miles from the coast, where the operations setup was set and from where the unmanned platforms were launched.

These tests aimed to 1) evaluate the motion capabilities of the developed UCAP, 2) to evaluate and refine the capability of the UCAP to be deployed from a larger USV, in this case the ROAZ USV and, 3) the capability of the UCAP to deploy a life raft in a specific and determined location. For these purposes an operational scenario was planned where at the first phase ROAZ USV would approach a determined area and launch at a specific spot the UCAP. The UCAP would navigate towards a specific point representing a victim location and at that point the UCAP would deploy the life raft.

On these first tests, the UCAP has proven to be able to navigate despite some difficulties during rotation. These are caused by the drag in rotation being very significant regarding the small rotation torque provided by the two thrusters, spaced only by 30 centimeters from each other. The motion capabilities and autonomous navigation capability were tested further posteriorly in La Spezia, therefore later in this paper this subject is further exploited.

Another important test was the capability of ROAZ to deploy the UCAP. The UCAP deployment system, introduced earlier in the paper, proved itself effective. These tests were useful to adjust the deployment system according the hull configuration and correct some issues. Deployments were successfully made, at the correct moment, triggered by the ROAZ on board CPU. The UCAP approach the water and was operational, capable of carrying out its mission. A video of this deployment is available at reference [7].

The tests made to the life raft deployment system by the UCAP were important to evaluate its performance under maritime conditions, with thermal and mechanical concerns, allowing the refinement of the system. Although the system allows a single shot solely, it revealed itself as an effective system for that purpose. The life raft was successfully launched from the UCAP. The automatic life raft inflation when deployed was not tested, that is a short term aim for the further developments.

B. Exercises On Coastal Sea Waters in La Spezia/Italy

The exercises in La Spezia, Italy, occurred between July 15th and 19th. These exercises, carried out in the Mediterranean coastal waters, occurred together with several entities participants on the ICARUS Project, namely the NATO's Centre for Maritime Research and Experimentation, who hosted the experiments, the Italian company Calzoni and the Belgian Royal Military Academy supervising the exercises.

As it happened in the Lisbon exercises the UCAP experiments aimed to 1) evaluate the motion capabilities of the developed UCAP, 2) to evaluate and refine the capability of the UCAP to be deployed from a larger USV, in this case the ROAZ USV and, 3) the capability of the UCAP to deploy a life raft in a specific and determined location. For these purposes an operational scenario was planned, identical to the scenario planned in Lisbon, where at the first phase ROAZ USV would approach a determined area and launch at a specific spot the UCAP. The UCAP would navigate towards a specific point representing a victim location and at that point the UCAP would deploy the life raft.

After further work according to the Lisbon results, and the refinement of the controller parameters, the UCAP was able to navigate in better conditions, even though the significant drag in rotation. It was evaluated the speed that the UCAP was able to reach for the different thruster actuations. Straight lines of about 40 meters were covered and the speed data given by the GPS was logged and analyzed. The maximum speed achieved by the UCAP was 1.39 m/s. For the different actuations (40% to 100%) the achieved speed is presented in the Fig. 10 in the form of mean speed and standard deviation for each actuation level.

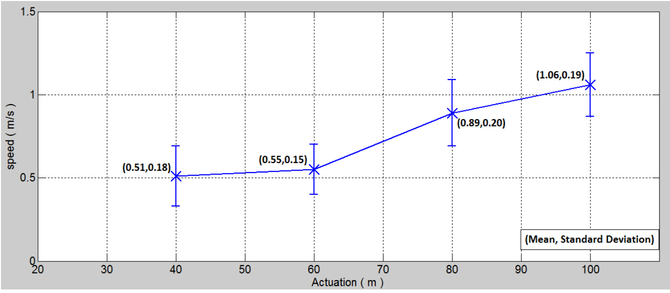

Fig. 10 - UCAPS achieved speeds for different actuations

In terms of rotation capabilities, as it happened in Lisbon, it was still noticeable some difficulties during rotation because of the very significant drag. The performed rotations achieved approximately 10 degrees/second in steady state, but this value can decrease with wind and waves interference.

To evaluate the autonomous navigation capability, it was given to the UCAP some waypoints to reach and had to do station keepings for large minutes.

Fig. 11 shows the behavior of the UCAP while navigating autonomously to a determined waypoint. The distance between the starting and the objective points was about 80 meters and the direction of the movement was west to east. The thrusters' actuation was limited to 60% so the average speed of the movement was about 0.55 m/s. The vehicle was able to carry its mission and achieve the waypoint, his trajectory suffered from off-track errors that did not exceed 2 meters.

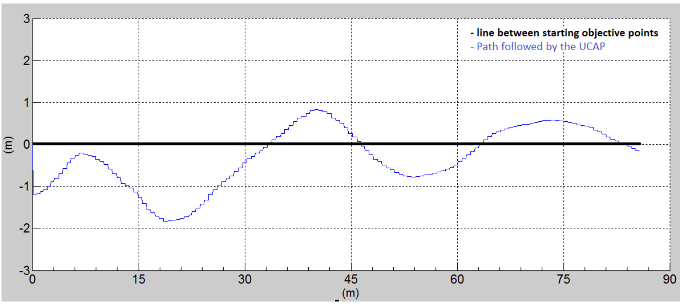

Fig. 11 - Autonomous navigation: straight line of 80m

Another important test to its autonomous behaviors was to evaluate its performance while in autonomous station keeping. In the Fig. 12 is presented the 2D positions of the UCAP, while trying to keep its position, compensating drifting movements caused by wind and currents for 25 minutes, with the reference point in the chart as the reference position. The drifting forces were pushing the UCAP to the western direction. The UCAP was able to keep near the point all the time, with a maximum error of about 7 meters. It is a good performance which allows concluding that the platform is able to keep in its position with a precision in order of a few meters.

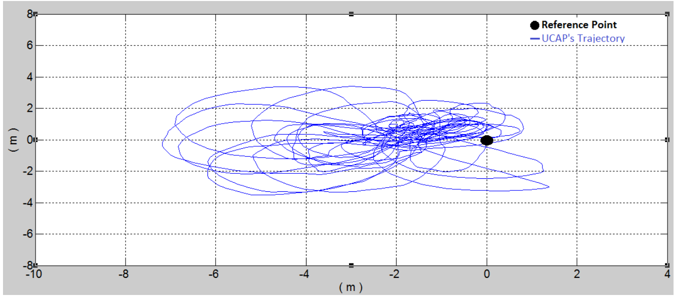

Fig. 12 - Autonomous Station Keeping for 25 minutes

The UCAP deployment system from ROAZ USV was tested further in La Spezia. As it happened in Lisbon successful deployments were made, at the correct moment, triggered by the ROAZ on board CPU. The UCAP approached the water fully operational, capable of carrying out its mission, see Fig. 13. After being deployed from ROAZ, the UCAP headed to a waypoint that represented a castaway position. When the UCAP achieved the castaway position it deployed the life raft successfully.

Fig. 13 - UCAP Deployment from ROAZ USV

VII. Conclusions and Future Work

This paper describes the developed Unmanned Capsule, the initial tests that the platform was submitted to and the respective results. Initial work has concentrated on the development of a platform capable of being deployed from a larger USV, capable of navigating and transporting lifesaving equipment, and deploying it in precise locations.

The experiments with the UCAP deployment system from a larger USV, in this case ROAZ USV, were useful to understand the suitability of the developed system and possible enhancements.

The life raft deployment system was partially tested, it was successfully tested the deployment capability of the life raft but it is still necessary to validate it while triggering the life raft inflation.

The motion and autonomous capabilities of the UCAP were experimented. Although the UCAP revealed to be able to navigate and perform autonomous maneuvers, and the basic requirements for this platform were validated, it is noticeable that there is still some work to be done in order to enhance the maneuverability of the developed platform.

The described work in this paper is a solid base for the next two years of developments in the scope of ICARUS. In the short term, the described platforms and systems will be reconfigured and refined. As mid-term developments the framework for communication and interaction between platforms will be implemented so that further tests can mainly focus on the coordination and cooperation between the several different platforms operating in the same scenario.

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