Use of multi-domain robots in search and rescue operations – contributions of the ICARUS team to the euRathlon 2015 challenge

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Abstract – *Search and rescue operations, in the aftermath of natural or manmade disasters, are complex and dangerous tasks that can benefit a lot from the use of robotics. Well known examples include the Fukushima and Costa Concordia accidents. However, a large gap exists between what is envisioned that robots can do, and what they effectively do in real situations.*

The ICARUS project is an EU funded project that addresses this gap. In this project various ground, air, and maritime vehicles were developed to work together in urban rescue and maritime disaster relief. Besides the project's planned field tests, the ICARUS team participated in an international competition, named euRathlon, was participant robots had to perform a pre-defined set of rescue tasks.

This paper describes the effort of the ICARUS team in the euRathlon competition. We start by describing the competition's tasks, and the vehicles that we used. We then describe the interoperability system that was used, and the results that we achieved. The ICARUS team received various awards, and was the only team to integrate all domains (ground, air, and maritime) effectively.

Keywords— Unmanned Vehicles; Search and Rescue, Interoperability

I. INTRODUCTION

EuRathlon Grand Challenge is a competition, inspired by the 2011 Fukushima accident, evolving teams of land, sea and flying robots cooperating and working together to fulfil the defined objectives like collecting environmental data, survey the scene or identify critical hazards. The Enel-owned thermal power station at Torre del Sale hosted a robotic competition involving all three domains: air, sea and land. The scene of a disaster was created: cooperating robots searched for workers in ruined buildings, leaks of substances and damages to underwater structures and other emergency response tasks, all in a race against the clock [1].

Intelligent robots for disaster response are an urgent need all over the world in terms of robotics research, industry and emergency services. euRathlon provides not only a place and time for researchers to meet and trade acknowledgments and experiences, as well as a platform to perform critical exercises and gaining experience in damage control and prevention in a cooperative way.

The ICARUS (Integrated Components for Assisted Rescue and Unmanned Search Operations) project is a large European research project with 24 partners from 10 European countries. It concentrates on the development of unmanned surface vehicles (USV), unmanned air vehicles (UAV), and unmanned ground vehicles (UGV) and search and rescue technologies for detecting, locating and rescuing humans. All these systems need to share information between them and interoperability is an important issue to take in account [2].

ICARUS Team brought to this event the LIFT VI, ROAZ, MARES, TEODOR and indoor oriented SUGV.

The remains of this paper are organized as follows: in Section II, we present the description of the scenarios. Section III, we describe the adaption strategy used in ICARUS vehicles. Section IV presents the air component. In section V we describe the sea component. In section VI the land component is presented. In section VII the results of integrating data are described. Finally we present some conclusions.

II. DESCRIPTION OF THE SCENARIOS

The scenarios are defined in three different categories: The Grand Challenge; Sub-Challenge and Trial.

The Grand Challenge consists of a three-domain scenario sea(S), land (L) and air (A) with three mission goals:

- Mission A: search for missing workers.
- Mission B: Reconnaissance and environmental survey of a building.
- Mission C: Pie inspection and stemming the leak.

To fully accomplish the Grand Challenge, the three missions should be completed within 100 minutes. As important as time limit, team strategy on how to use their robots played an important role on the mission success.

The Sub-Challenge is a two-domain scenario which are similar to the GC scenarios although with slight differences:

- Sub-Challenge (L+A): survey the building and search for a missing worker.
- Sub-Challenge (S+A): Pipe inspection and search for a worker.
- Sub-Challenge (L+S): Stem the leak.

The scoring takes into account not only the time limit, but also how well a robot performs in a specific task and how good a robot performs in terms of autonomy.

The Trials are divided in two for each domain: two land trials, two sea trials and two air trials.

III. INTEROPERABILITY

Interoperability may be defined as the capability of robots to operate in synergy for the execution of assigned tasks by sharing data, intelligence and resources. To ensure interoperability, ICARUS proposed the adaptation of the different platforms to a single standard interface [3]. The ICARUS standard interface then, acts as the glue among the different technologies of the ICARUS team [4]. It is based on the Joint Architecture for Unmanned Systems (JAUS) which is fairly aligned with the ICARUS purposes.

To be interoperable with the ICARUS team, a new system can directly integrate this interface. However, most robotics platforms currently are based on either proprietary or open-source middleware's. To integrate a new system then, an alternative is to implement an adapter to the robot-specific middleware. Figure 1 illustrates both cases: robots A and B are using their own middleware while robot C is natively integrated.

ICARUS developments are heavily based on the end-users feedback. According to end-users, SAR teams (search and rescue teams) are irremediably faced with a massive overload of work, so "sacrificing" people to operate the robotic tools is not an easy compromise. Therefore, a single Standard Command, Control and Intelligent (C2I) system was developed to operate the different systems in a mission.

The ICARUS project has validated the interoperability standard through a sequence of trials where the different collaboration between robots where tested at task and mission level. An initial integration of each unmanned platform and the C2I served as a
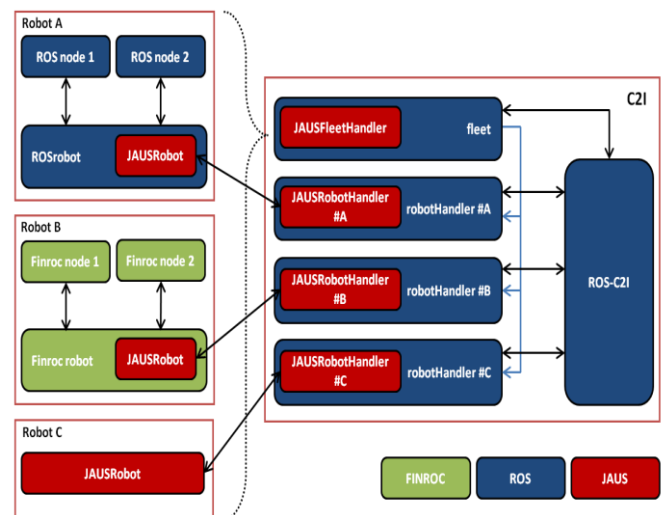

Figure 1 - ICARUS robots integration strategy

benchmark for verification of the ICARUS standard interface.

In the end, all vehicles, in all domains, were tasked and controlled using a single ICARUS Console, and a common communication system. This is a clear step forward and simplifies greatly the operations and training process of rescue personnel. After corrective actions were applied, interoperability between ICARUS platforms was validated in real operations on search and rescue scenarios.

For ICARUS, the euRathlon competition was a further opportunity to validate the developments of the project in a realistic scenario that was not specified and prepared by the project itself. EuRathlon also allowed demonstrating how easily a robot can be integrated in the ICARUS network. Two new robots were used by the ICARUS team. TEODOR, a large ground robot provided by RMA and MARES an underwater robot provided by INESC.

IV. AIR COMPONENT

ICARUS follows a collaborative multi-stage approach for the aerial assessment of the disaster zone with multiple and complementary aerial systems (fixed-wing and outdoors and indoors multirotors). However, only one of the aerial systems could participate in euRathlon according to the rules of the competition: an autonomous outdoor coaxial quadcopter. The platform is called LIFT VI (Figure 2) and has been developed by Eurecat-ASCAMM Technology Center to satisfy the needs of Search and Rescue operations.

Figure 2 - ICARUS team UAV

LIFT IV has a 855 mm diameter and weights 4.3 Kg. The propulsion chain has been optimized to maximize the payload capacity (3.8 Kg), endurance (approx 40 minutes) and wind resistance (up to 35 Km/h). The system incorporates the Eurecat "Copilot" as illustrated in Figure 3 which is a payload designed specifically for Search and Rescue operations, integrating an onboard computer, a stereo vision-inertial sensor, a thermal imager (FLIR Tau2), and a mechanism to deliver survival kits to the victims. These features allow the automatic detection of victims, obstacle avoidance, fast mapping, 3D reconstruction and other added value functionality. All sensor data is automatically available at the C2I. The following image (Figure 4) shows the real time detection of the "Unblocked entrance" on the quadrotor.
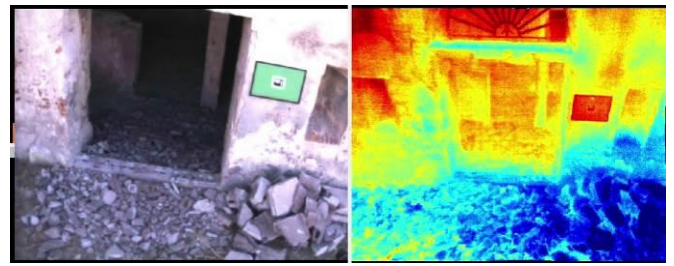
Figure 3- Eurecat MAV Copilot

Figure 4 - Unblocked entrance detected on thermal and visual camera

V. SEA COMPONENT

The sea component used the ROAZ autonomous surface robot (Figure 5) and the MARES autonomous underwater vehicle (Figure 6). These two robotic systems provided complementary capabilities for the sea challenges and were used in cooperation.

The ROAZ unmanned surface vehicle is a 4m long, 2m wide catamaran type of vessel with electric propulsion capable of operating at sea. Its navigation system uses an on board fiber optic (FOG) INS system and a precise RTK GPS receiver thus allowing for accurate geo-referencing of sensory data [2].

On board processing capabilities allow not only for control, navigation and mission execution but also for sensor data processing such as autonomous detection of mission relevant events.

The vehicle as a set of surface mounted sensors (mounted on the bridge in Figure 5) such as visible spectrum and infrared cameras, a RADAR and a LIDAR sensor for close range environment modelling.

Underwater, it carries a single beam echo sounder, a multibeam and a side scan sonar. These sensors are used for seabed 3D modelling and bathymetry tasks.

Figure 5 - ROAZ Unmanned Surface Vehicle

The MARES (Modular Autonomous Robot for Environment Sampling) autonomous underwater vehicle is a 1.5 meter long, 20 cm diameter vehicle capable of hovering operations with an 10hr of autonomy and diving up to 100m. This highly manoeuvrable vehicle has a digital video camera with on-board video processing. It also possesses a downward looking echosounder, a pressure cell and a inertial measurement unit, as basic navigation sensors. An acoustic LBL

navigation system can also be used for geo-referenced operations.

Figure 6 - MARES Autonomous Underwater Vehicle

ROAZ unmanned surface vehicle provided an initial survey of the area providing an initial bathymetry map along with possible points of interest to be searched by the AUV. This allowed for a relative fast coverage of the area and also was used as an input for the MARES AUV mission definition.

After the initial survey, MARES starts its mission diving already near one of the possible points of interest. With the on-board camera an underwater survey is performed and automatic detection of the relevant targets (human victim, plume leaks or piping structures in this case) is performed. All the logged images are geo-referenced using information from the AUV navigation system, thus allowing the posterior location of the targets.
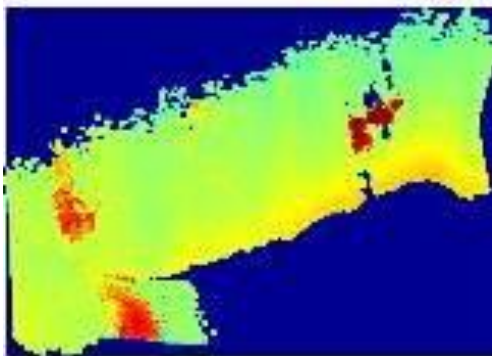

Figure 7 - Initial survey map made by ROAZ USV in one of the trials

In the previous figure (Figure 7) one example of one of the initial multibeam surveys is presented. The map shows the location of possible underwater structures of interest signaled in red.

On the following picture (Figure 8) an image taken by the AUV of one of the required targets (pipe entrance) is shown. The timestamp of all the data allowed for position correlation and location of the targets.

Figure 8 - Underwater pipe structure image taken by MARES AUV

VI.   LAND COMPONENT

The land component of ICARUS team consists of two mobile platforms: heavy, outdoor oriented TEODOR and indoor oriented SUGV. During a mission the platforms cooperate to fully utilize strong points of both. TEODOR is equipped with a mapping system dedicated for gathering 3D data about the mission area. The system consists of rotating SICK LMS 500 scanner and LadyBug spherical camera. The data provided by the system are 3D point clouds and spherical images. Images are recorded during full robot operation while 3D data are gathered in stop-scan fashion.

During the competition TEODOR was responsible for transporting the SUGV and gathering data about the mission area. Transportation was done by using a custom made trailer that automatically disconnected from TEODOR when SUGV moved away from it. The whole setup is shown in Figure 9. After release SUGV's main tasks is to perform inspection of indoor area and cope with and manipulation tasks required. This vehicle also uses tracks but is very nimble, and is equipped with a long arm manipulator capable of fine movements to pick up objects or manipulate valves.

Figure 9 - ICARUS team land components: TEODOR (the green tracked vehicle), and SUGV (the orange vehicle in the trailer).

After releasing the smaller robot TEODOR's main task was to create a 3D map of the outdoor section of the mission area. The map is built online during robot operation. To achieve online operation single 3D scans have to be down-sampled (from ~300.000 to 3.000 points). An unfortunate side-effect of this approach is lower accuracy of the 3D model. This mapping framework can enhance the map in posts-processing, after the mission. Enhanced maps can achieve accuracy of up to 1 cm and have a density similar to densities of single scans.

One of the most important side tasks in the competition was detection of OPI's in the mission area. With ground platforms an approach with 3 separate layers was used:

- Automatic detection – the cameras of the robots were connected to automatic detection software that recorded found OPI's in kml file.
- Operator detection – robot operators were equipped with tools for reporting and identifying OPI's. The tools allowed user to place the OPID on a georeferenced map and saved info in kml file
- Post-Processing detection – final layers of detection was done in post-processing by analyzing recorded LadyBug stream for potential omitted OPI's. This approach proved to be especially successful for OPIs that were in places with limited visibility.

Figure 10 - Example of automatic OPI detection in image.

Figure 11 - Spherical image from Ladybug camera

The main problem the ground platforms faced was communication. Both platforms used a 2.4 MHz WI-Fi connection. This significantly lowered the reliability of the connection for higher ranges and indoors. Use of repeaters did not significantly improve the situation. Major improvement was noticed after changing part of the robot's antennas so as to better use reflections instead of direct signals.
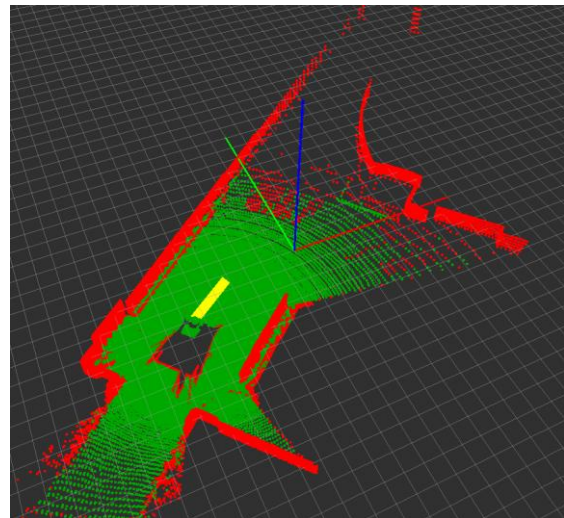

Figura 12 - Traversability map generated based on single scan; red – non-traversable, green – traversable

TEODOR platform is able to operate in semi-autonomous modes during mapping. The approach used is based on 3D point cloud data. Path to new scanning position is computed based on the last scan. In that mode robot travels about 2 – 3 meters between scans. This distance is one of key parameters. Operator is able to define waypoints in latest local scan. During autonomous operation the system goes through following steps in a loop:

- Scan of environment - Laser scanner needs to perform full revolution. It takes about 10 seconds.
- Point cloud registration – Latest scan is localized and matched to previous scans. After this step robot is localized, and consistent map of environment is updated.
- Scan cropping, subsampling and normal vector

computation - In this step the scan is cropped to remove points which are not important (higher than robot) for traversability reasoning. Point cloud is also down-sampled to achieve uniform density, which is important for proper normal vector computation.

- Scan classification - in this step points in the cloud are classified into two classes: traversable and non-traversable. Traversable points are those which lay on ground. Classifier uses data provided by normal vectors.
- Non traversable areas are projected on XOY plane
- 3 step - 2D inflation of map - 2D inflation (dilation with circular kernel with given radius) allows to simplify robot to a point in next steps. Added next inflation level with smaller weight prevents approaching obstacles.
- Generation of trajectories - Control space of the robot is discretized and constrained with minimal and maximum angular and linear velocity, and maximum angle.
- Trajectories simulation - For every generated trajectory R(v_a,v_l) in control space a trajectory is generated in output space R(x,y,fi).

- Trajectory are projected on 2D map and weighted.
  Trajectory weight is sum of map cells' weights which trajectory contains. Also trajectories get penalty points if angular velocity is high. Additional penalty points are given if end of trajectory does not point to the goal.
- Trajectory with lowest weight is send to robot controller, if obtained weight is lower than threshold.
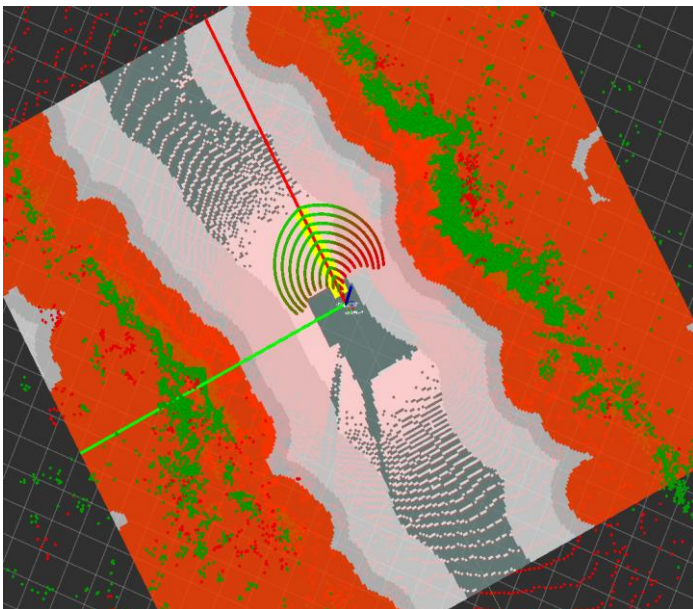

Figure 13 - Map after inflation with potential trajectories.

VII. RESULTS

All vehicles performed as planned in their specific tasks, but the most relevant contribution of the work done by the ICARUS team came from the way all cooperated and integrated with the common control station to achieve the final results.

Thanks to the ICARUS interoperability, all the robots were able to provide live data during the operations. Given this, every operator was aware of the performance of all the robots as there was constant communication between domains. This fact made possible several achievements:

- The large ground robot was able to directly go to the unblocked entrance of the building. It was possible because the outdoor quadrotor detected quickly the unblocked entrance and communicated it to the land operator.
- The small ground robot and the underwater robot detected the correct valves of the leaking pipes. This operation was needed to be in synchronization. All operators communicated to the others the correct leaking pipe as soon as the robot had detected it.
- Every operator was aware of all the OPI's already detected, including missing workers, blocked and unblocked entrances and damages in the environment.
- A cooperative mapping mission was done, fusing data from the ground and aerial vehicles [5].

The results from each domain were fused using the C2I and provided to the organizers for their evaluation. The following image shows the result from the Grand Challenge, with the multi-domain maps, the trajectory of the different robots, and the evidences of the automatically detected OPI's (objects of potential interest).
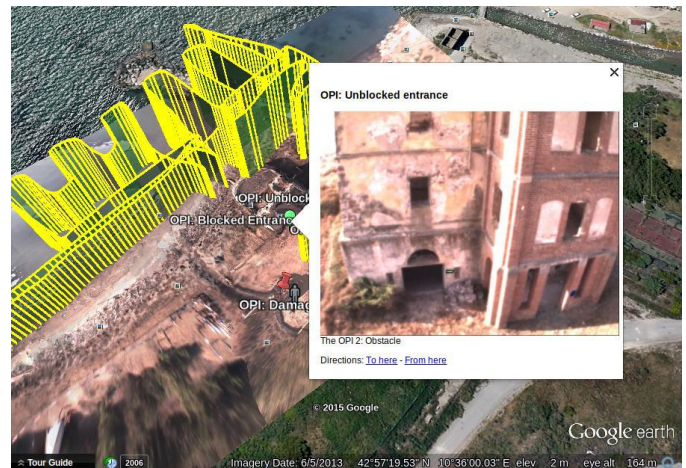

Figure 14 - Fused results from air and ground

3D data gathered by different platforms can be merged into a single 3D map of the environment, like

Figure 14. The model created with this approach has advantages of both aerial (high coverage in short time) and ground (high accuracy) mapping. Figure 15 shows two maps as different layers, while Figure 16 shows the merged map. Algorithms used in merging process are described in [3].

Figure 15 - Two layers of 3D map; Top – ground, bottom aerial data.

Figure 16 - Merged aerial and ground point clouds.

VIII. CONCLUSIONS

The ICARUS team managed to make a team of diverse and multi-domain autonomous vehicles achieve together the objectives of the euRathlon competition. Not only did each individual vehicle perform it's task, but the result of integration provided a real added value, in terms of improved situational awareness (and associated benefits) and ease of operation. The good results were recognized by the awards given.

The major difficulties encountered during the competition concerned communications with the vehicles. Lack of connection with vehicles leads to problems even in autonomous mode as the operator cannot oversee robot operation and intervene in critical situations.

Use of 3D laser and 360 cameras provides a major improvement in operators understanding of the scene. Even low quality images of the whole surrounding areas provide more information about the general robot situation than normal quality classical cameras.

In situations when connection with the robot has a high delay 3D point clouds are a good alternative for cameras. Lower refresh rate (0.1Hz in comparison with 30 Hz of standard cameras) requires lower bandwidth and detailed geometrical information about immediate surroundings allow to perform semi-autonomous operation.

Detailed 3D models and spherical images gathered during platform operation provide a major improvement to global situational awareness. The level of detail provided by the data makes them valuable for mission planning, evaluation and possible repetition.

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