Search & Rescue

Emerging technologies for the Early location of Entrapped victims under Collapsed Structures & Advanced Wearables for risk assessment and First Responders Safety in SAR operations

D5.8 Testing of RESCUE MIMS on-board robotic platforms and drones

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Table 2: List of Abbreviations

Abbreviation	Explanation
AC or ac	Alternating Current
Cat-6	Category 6
CCTV	Closed Circuit Television
FAT	Factory Acceptance Test
FOC	Fibre Optic Cable
FOV	Field of View
GPS	Global Positioning System
GLONASS	Global Navigation Satellite System
HMI	Human Machine Interface
ICD	Interface Control Document
IEEE	Institute of Electrical & Electronic Engineers
IP	Internet Protocol
IVVQ	Integration, Verification, Validation and Qualification
IT	Information Technology
ITU	International Telecommunication Union
LAN	Local Area Network
LCD	Liquid Crystal Display
LED	Light Emitting Diode
Lipo	Lithium Polymer
Mb/s	Megabits per second
MIMS	Membrane Inlet Mass Spectrometer
ODS	Obstacle Detection System
PoE	Power over Ethernet
RTMP	Real-Time Messaging Protocol
S&R	Search and Rescue
SAT	Site Acceptance Test
SDK	Software Development Kit
TCP/IP	Transmission Control Protocol/Internet Protocol
UC	Use case

Executive Summary

The Task 5.4 called "Testing of RESCUE MIMS on-board robotic platforms and drones" is an activity lead between Month 10 and Month 30 in the Project Search & Rescue.

The main scope of T5.4 is to test the robotic platform provided by DFKI with its sensors (Cameras and LIDAR), the Obstacle Detection System (ODS) provided by THALIT and the field chemical tool (RESCUE MIMS) provided by the NTUA together with the drone provided by UHasselt.

In order to share all the possible interface from Telecom, Power, Physical and Logical point of view a dedicated Interface Control Document has been developed in order to align all partners on the mutual interfaces.

Within the Task 5.4 some specific tests are foreseen, for example the ODS algorithm will be tested with some images provided by the end users, the robot will be tested with a dedicated test and the RESCUE-MIMS will be tested in lab-scale experiments

The related deliverables foreseen in the Task 5.4 are two: the D5.4 "Testing of RESCUE MIMS on-board robotic platforms and drones" (this document) where the topic is introduced as per status of the project and the D5.8 "Testing of RESCUE MIMS on-board robotic platforms and drones, V2" that is the revision 02 of the D5.4 with the possibility to finalize all paragraphs not ready at the moment of the D5.4 release.

The main objectives and outcomes of the D5.8 "Testing of RESCUE MIMS on-board robotic platforms and drones, V2" are the description of the platform robot with its sensors (Cameras and LIDAR), the Obstacle Detection System (ODS), the field chemical tool (RESCUE MIMS) and the drone; in particular it is described the integration and the interfaces between all these components following the activities of Task 5.4. Moreover, it is introduced the testing procedures of the whole technological platform and at the end the test reports.

The milestone submission of D5.8 is at the end of Month 30, moreover the Use Case where all the components will be tested together is the number 4, named "Forest fire expanded and threat to industrial zone (Corinthia, Greece)" that is foreseen in November 2022.

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1 Introduction

The following paragraphs introduce the state of the art in chemical sensors tests with robots and drones in order to have an overview of the subject matter, then the possible improvement that could inspire the S&R Project and finally the introduction of the S&R Robot and Drone Work Plan foresee in the T5.4 and the related S&R Proposal.

1.1 State of the art

In case of natural or technological disasters, there is a strong possibility of hazardous environments formulation, not only for the affected communities and the people who are exposed but also for the first responders that are the ones who are called to mitigate the phenomenon at its early stages and limit the impacts.

Air quality monitoring in such cases can be proved vital for assessing the risk of exposure to dangerous compounds and hence, help the decision makers in the disaster management e.g. decide on the evacuation of the affected area, or for using specific personal protective equipment etc. In case of technological or fire incidents, chemical sensors or biosensors and unmanned platforms (UAVs or UGVs) could be used as a remote early warning system for the safety and security of the first responders that are engaged in the field, through detection of selective hazardous smoke components, known as Critical Key Indexes-CKIs [1-3].

Worldwide, there is a significant increase in the use of unmanned aerial vehicles (UAVs) by emergency services since they can support the rescue operation and Specific Operations Risk Assessment (SORA) [4]. According to literature, there is a possibility of recording chemical data on-line as maps of pollutants' concentrations for the areas of interest with the help of drones, as shown in Figure 1 [5] "Gas concentration map of an area monitored by a drone equipped with a photoionization detector (PID)."

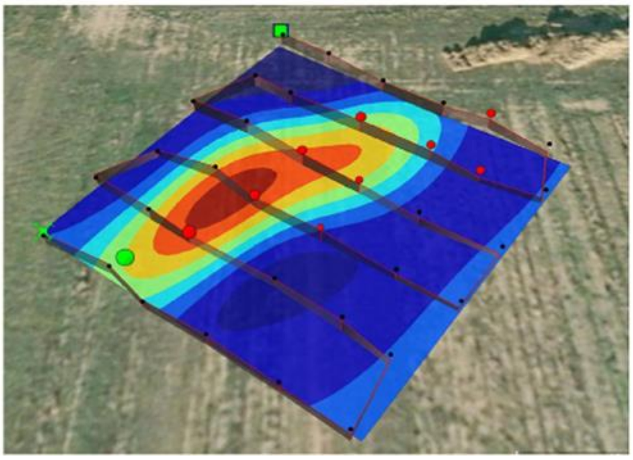


Figure 1: Gas concentration map of an area monitored by a drone with a photoionization detector.

However, there is a number of limitations in using drones with chemical sensing technologies, especially the small ones, such as their limited payload capacity and the short flying times (usually 15–20 min) that make them inappropriate for large-scale screening in settings with low infra-structure density; obstacle detection and avoidance is still not feasible in realistic scenarios [5].

Concerning the ground robots, there is a variety of them that have been used in Search and Rescue operations, such as snakes, tracks and legged locomotion [6-7]. These types of robots can be used on rough terrain, which is usually encountered in rescue missions, though they are also fairly slow. Since operation speed is quite important for searching for potential victims after disasters, these types of robots are usually used in swarms to search an entire area in coordination; it requires interconnectivity and/or sensor data fusion during the operation [6-8]. According to literature, different types of unmanned aerial vehicles and ground robots with chemical sensing have been tested together for their interoperability under a forest fire scenario [2]. It seems that robotic platforms can be assigned different missions like damage inspection, or even medical assessment of victims and for transporting equipment and first aid kits [9].

1.2 How to improve the State of the Art

It seems that chemical sensing on-board robotic platforms, like drones is a promising tool for a number of applications, such as environmental, or for safety and security purposes [10]. Also, drones have been used in a variety of S&R emergency services and in many research projects like INACHUS, AirBorne, DARIUS etc [11-13].

However, it has to be noted that a crucial issue when using a chemical device as a payload on a drone is the thermodynamics (turbulence), the vibrations and in general how the high altitude in terms of increased RH%, low temperature and increased atmospheric pressure may affect the response of those devices e.g. operation of pumps, sampling rate, response times etc. Also, the speed of a platform, either aerial or ground, is a critical factor for providing with spatially resolved measurements and it mainly depends on the frequency that a chemical sensor can sample [14]; a dynamic inlet system is required for monitoring dynamic changes of concentrations in time and space. Testing of chemical sensors by monitoring the above parameters could improve the state of-the-art in chemical sensing with robotic platforms.

Another important issue is the downwash generated by the propellers of Rotary-Wing (RW) drones can that can affect the concentration density of the chemicals that are monitored and hence, the quality of the measured data (false negatives) [5]. This is also an issue to be considered when using chemical devices on-board ground platforms, e.g. vehicles (roving systems) because measurements can be affected by the exhaust emissions of the vehicle providing with false positives; electric-powered vehicles are preferred for that reason.

Obstacle avoidance algorithms also seem substantial to support the robotic platforms in semi-autonomous movement operations. Search and rescue drones need to have additional requirements comparing to other generic drones. These requirements include a long flight time, a good payload capacity and a high resistance to environment and weather conditions (e.g. to 28.8km/h wind speed and more than 40°C temperature operating temperature). According to literature, Fixed Wing UAVs, capable of flying in moderate winds, can be used effectively in forest fires and especially in S&R operations [2]; according to the same study, ground robots need to be fireproof and heat resistance.

1.3 S&R T5.4 Work Plan

The scope of the Task 5.4 is the "Testing of RESCUE MIMS on-board robotic platform and drones". The following main activities explain the related work plan in order to achieve this scope:

1. Components identification by each partner following by alignment meetings.
2. Data gathering between partners in order to collect and to compare the proposed components.
3. Organization of related technical meetings in order to introduce and analyze all the interfaces and connections from any point of view: Telecom, Power, Data and Physical.
4. ICD (Interface Control Document) submission as internal Project document.
5. Definition of the resulting architecture with the identification of each role for each partner and for each component.
6. Integration and Testing.

2 IVVQ Methodology

The following paragraphs describe the IVVQ (Integration, Verification, Validation and Qualification) methodology including the introduction of the theoretical approach with V-Cycle Scheme, the management of the interfaces on the Robot platform and Drone with the ICD document, the related interface Matrixes and finally the S&R Robot & Drone Integration and Verification Plan.

2.1 The V-Cycle Scheme

The V-Cycle scheme is a model usually considered in the IVVQ strategy that represents the theory of the systems development lifecycle within the System Engineering and Project Management disciplines. In particular, it is applied for complex Integration System in an industrial context.

The Figure 2 shows all the steps and the dependences foreseen on the V-Cycle scheme:

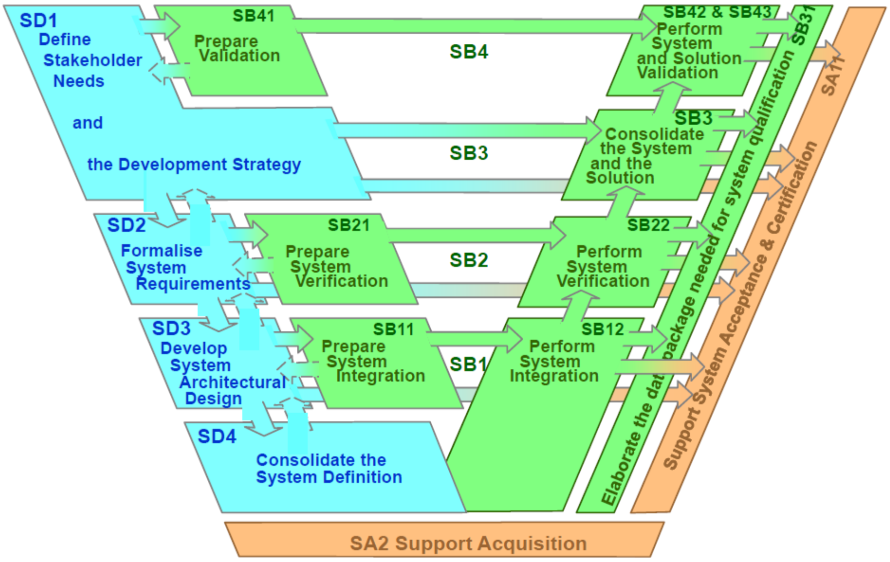


Figure 2: V Cycle Scheme

The SD1 is the step at the beginning of the Design and it is fundamental in order to well define the Stakeholder Needs and the consequent development strategy; in particular the needs can come from customer "nice to have", formal specifications and/or from experience of who is the provider of the System that will suggest the right need.

The SD2 is the second step useful to formalize the System requirements; these are not be confused with the Stakeholder Needs, in fact these are the list of the technical issues to achieve the Stakeholder Needs. Often only the system engineer knows the constrains, the performances and the activities to reach a Stakeholder Need.

After the formalization of the System requirements, the related System Architecture can be designed and developed with a block diagram (SD3) and the System definition (SD4) can be consolidated for example with the submission of a Functional Design Specification.

It is important to perform a review at the end of each step, an internal review and/or with customer in order to search eventual issues and to consider a new revision of the previous step.

At the bottom of the V-Cycle, the activity SA2 Support Acquisition is often considered the "point of no return" of the design and development, in fact this will produce the Contracts with outside companies (vendors) and the eventual manufacturing will start.

As shown in Figure 2, the parallel activities to the left side of the "V" can proceed, then for example; following the architecture the preparation of System integration (SB11) can be prepared with related document and consequently the System integration can be implemented (SB12).

"Prepare System Verification" (SB21) and "Prepare System Validation" (SB41) mean to write the documentation that will describe the related phase of testing, usually procedures are submitted. An important note is the difference between Verification, which is the test statement by statement of all requirements, and Validation, which is the test statement by statement of all Stakeholder needs.

Passed all the steps also on the right side of the "V", the activity for System Qualification (SB31) can be performed, this could push the related manufacturing. Finally, the Acceptances and/or Certifications (SA11) can also be performed. In particular, the step of Acceptances are usually two: the first is the FAT (Factory Acceptance Test) and the second is the SAT (Site Acceptance Test), which follows the Verification and the Validation with the Customer presence.

The arrows that go from the left side to the right side of the "V" define Requirements Traceability, in fact that from requirements to preparation, are called the "Link to Design", that from requirements to verification/validation are called the "Link to Test". The Test Procedure will be derived directly from the Requirements Traceability and developed in the revision 2 of D5.4 (this document) in Paragraph 7.2.

2.2 S&R T5.4 – Interface Control Document Results

During the first 12 months of S&R Projects several meetings have been organized in order to introduce and analyze the Interfaces of all components for the Robot and the Drone platform. Then, the Interface Control Document has been issued with the definition of all interfaces and connections from Telecom, Power, Data and Physical point of views. The ICD has contributed to define the resulting architectures, including the identification of each role for each partner and for each component. The following paragraphs report the results of the ICD document.

2.2.1 ICD – Components positions and related provider partners

The following Figure 3 shows the mutual positions of single components:

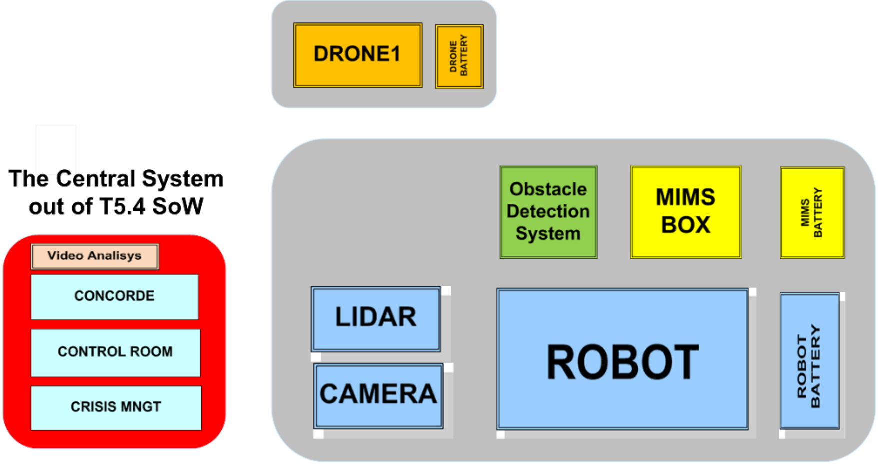


Figure 3: Components mutual positions on Robot and Drone platform

In particular, LiDAR sensor, Camera, Robot and its battery are provided by DFKI and the Robot will host the Obstacle Detection System provided by Thales and the MIMS with its battery proved by NTUA. The Drone with its battery provided by UHASSELT will be independent from Robot platform and the related Video Analysis provided by Aideas will be installed on the Central System (out of T5.4 Scope of Work).

2.2.2 ICD – Telecom connections Block Diagram

The following Figure 4 shows all Telecom connections foreseen in the Robot & Drone platform:

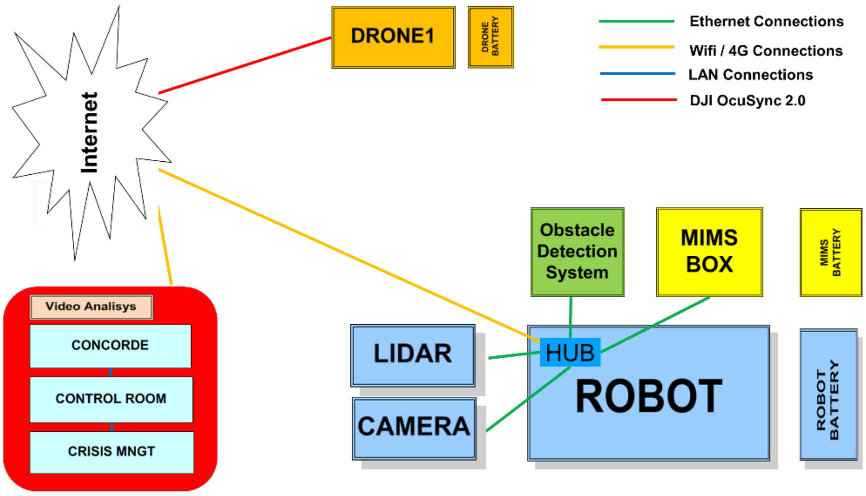


Figure 4: Telecom preliminary Block Diagram

In particular, all sensors (LiDAR sensor and Cameras) and devices ODS and MIMS box will be connected together with an HUB provided by DFKI which will be connected to the Control Room via WiFi or 4G connection, the Drone will be connected to Control Room with a specific telecom connection. For details on the architectures refer to the paragraphs 4.2 and 5.3.

2.2.3 ICD – Power connections Block Diagram

The following Figure 5 clarifies the power feeding of the single components on Robot and Drone platform. In particular, the MIMS and the Drone will have the own batteries, while the Obstacle detection System will be powered by the Robot battery.

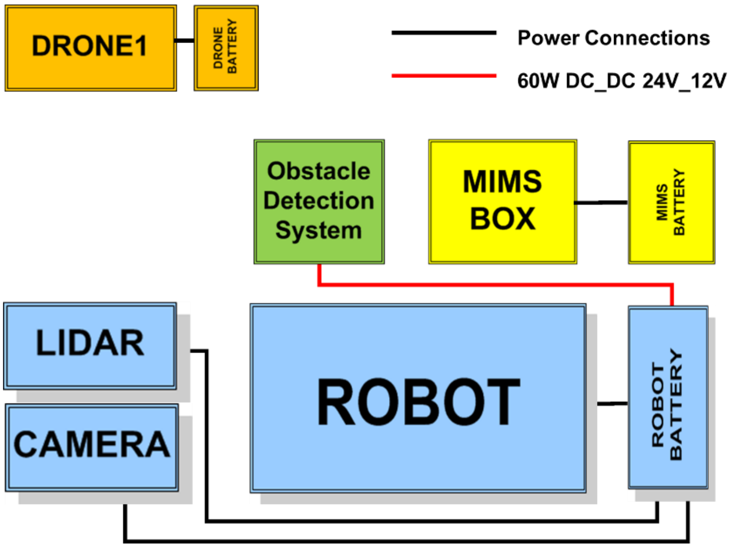


Figure 5: Power Connection Block Diagram

2.2.4 ICD – DATA connection Block Diagram

The following Block Diagram provides an idea of all data exchanged within the Robot and Drone platform:

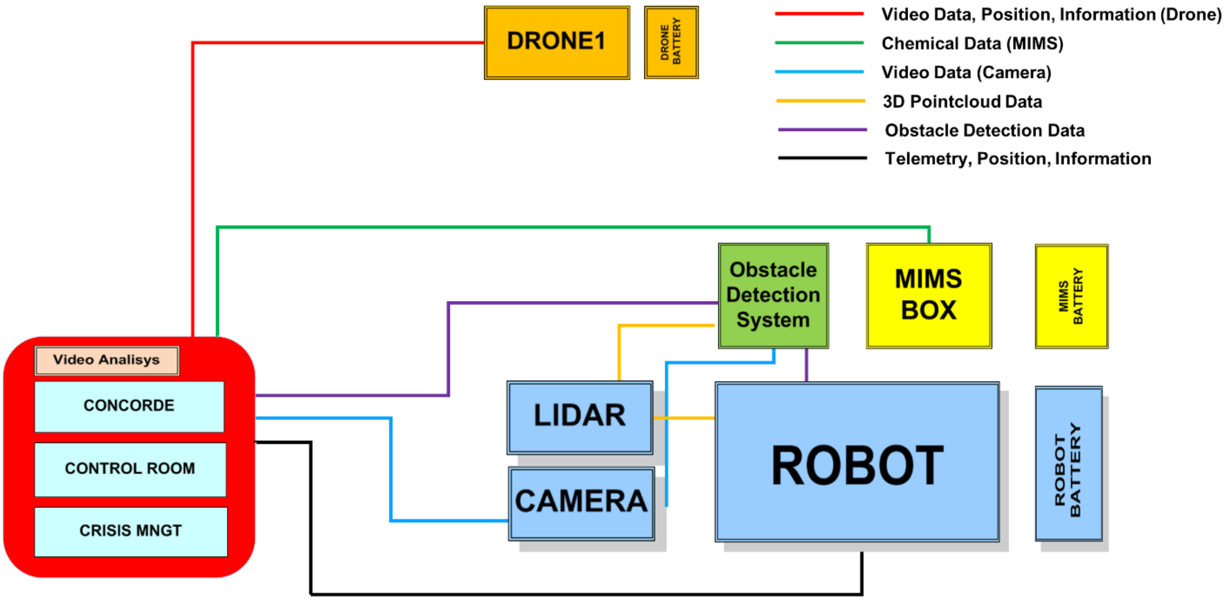


Figure 6: Data Connection Block Diagram

2.2.5 ICD – Physical connections Block Diagram

The last figure of this chapter (Figure 7) explains the physical connections to be organized on the Robot and Drone Platform, for example the connection between Obstacle Detection System and the Robot will be through metal brackets (the same possibly for the MIMS):

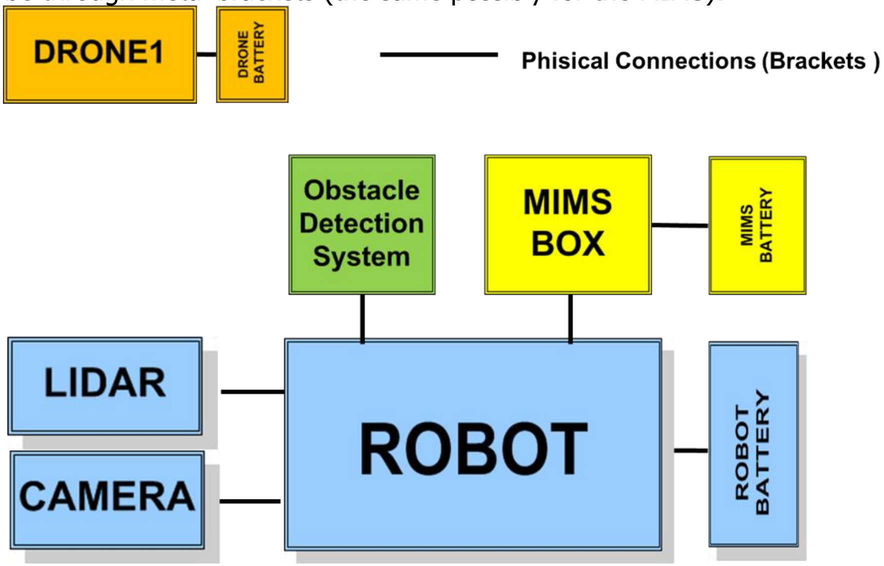


Figure 7: Physical Connections Block Diagram

2.3 S&R T5.4 - Integration and Verification Plan

The Integration and Verification strategy takes into consideration the V-Cycle scheme with the adaptation on the context of the S&R Project. In particular, the project is characterized by several partners that have the responsibility of a single component.
Following a lean approach, the strategy is to anticipate as much as possible all feasible test in house and to consider the integration test of the Robot as the key point of verification of the integrated design to de-risk the validation phase on site in the Use Case 4.

Refer to the following flowchart integration and testing plan, where the FAT is a preliminary preparation test (refer to 6.1 and 6.2) for each component, the i-FAT is integration test in the Robot platform while the SAT is the final test during the Use Cases:

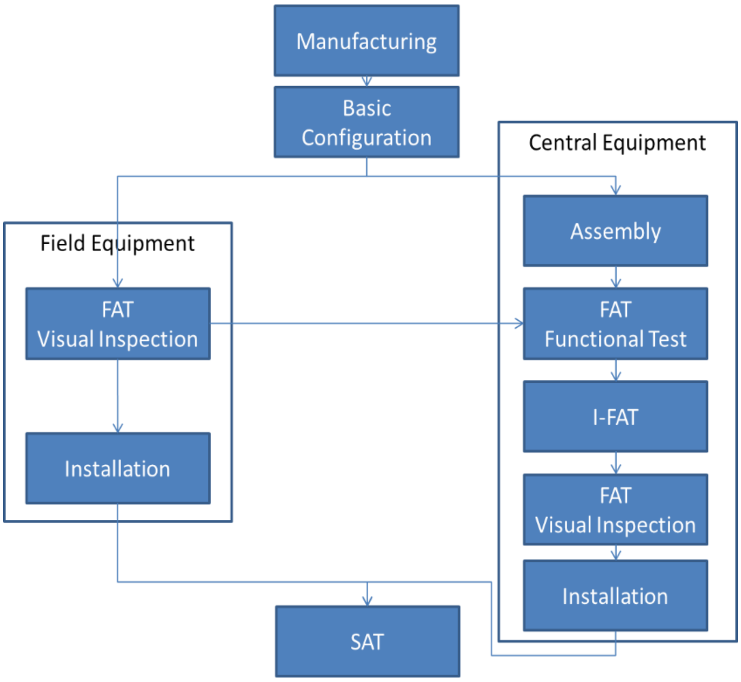


Figure 8: Integration and Testing Flowchart

Moreover, in order to anticipate any integration SW issues, an additional remote test is foreseen between Robot, Obstacle Detection System and MIMS box to test for example the robot inputs from Lidar and Camera towards ODS or the output of ODS toward the Robot.

3 Solutions Composition

3.1 End-Users opinions (from WP8)

In the context of WP8 in the S&R project the questionnaire "Need for use cases' technologies" has been launched between the End Users, hereafter the main statements about the Robot Platform and Drone are listed in order to have the important point of view of the End-Users:

Question: Are there any components/technologies that are missing that you would like to have?
Reply: No, everything that is going to be used or not used from the proposed solutions came up after serious consideration

Question: What are the main constraints (i.e. obstacles that these technologies could pose during use cases) that you think these technologies could entail in the use cases?
Reply: Wi-Fi network and 4G might pose a constraint. Also weather might be an obstacle and flying of drones might not be feasible.

Question: Is it required special maintain costs or efforts for the selected technology?
Reply: Yes. Maintenance, insurance (for the drones), batteries, data for mobile network, etc.

Question: Does it require a complicated bureaucracy / or legal framework for its implementation?
Reply: In some cases yes. We need special permissions to fly the drones.

Question: What real change will it bring to Search and Rescue Operations?
Reply: Saving time. Supporting a more efficient way on carrying out the Search and Rescue operation.

Question: Is there a component could be improved in the selected technology in order to be more efficient and what reason?
Reply: Chemical sensors, since we are involved in UC where there is a chemical risk and robots to assess the risks before FRs interventions.

Question: What is the combination of technologies that are envisaged in each use-case? (i.e., Rescue MIMS combined with robot and obstacle avoidance system; drones with artificial intelligence, etc.).
Reply: Chemical sensors in combination with robots and drones. Six gases monitor in combination with drones and robots.

Question: What technologies are most and least important to you/your organization?
Reply: Most relevant: Rescue MIMS, Emergency Response health condition monitoring device (especially for us as EMS), drones/robots (for data gathering e.g. of hard to reach places)

Question: Is the select technology easy to use?

Reply: The use of robot and obstacle avoidance is depending on an external pilot

Question: Is there a component could be improved in the selected technology in order to be more efficient and what reason?

Reply: The weight and the volume of the MIMS could be improved in order to be transferred more easily from a drone. The new tools could be communicated before the UC to be known from the teams before the use case.

3.2 Operative Scenario (from WP8)

As introduced in the paragraphs above, all the components of T5.4: the robotic platform provided by DFKI with its sensors (Cameras and LIDAR), the Obstacle Detection System (ODS) provided by THALIT and the field chemical device (RESCUE-MIMS) provided by the NTUA together with the drone provided by UHasselt will be tested together during the Pilot UC4: "Forest fire expanded and threat to industrial zone (Corinth, Greece)".

The pilot will take place in an urban area mixed with forest that is situated nearby an industrial zone. It has to be considered that wildfire disasters may rapidly change their nature into technological disasters, e.g. in the mixed areas of forest and residential, heavy industrial, or recycle zones. This pilot is based on a real scenario that took place in Industrial Zone, Greece were a refinery was indeed in danger during wildfires occurred in July 2018.

The main objective of the pilot is to test the remote sensing technologies proposed in the S&R project for the safety of first responders; alarms for early warning of toxicity or radiation exposure and generally inspection of the hot zone area; use of rescue robots and drones to facilitate the SAR operations.

The estimated time for the implementation of UC4 is November 2022. The pilot will take place a Weekend during the daytime, at 8.00 a.m. and last 8 to 10 hours, in a region called Lecheo close to city of Corinth. The place of the pilot will be the LECHEO (LEH), Military airport, Corinthia. Longitude: 22o 51' 40.15" E. Latitude: 37o 55' 38.37" N

All components that will be tested are:
1) Smart Glasses (SIMAVI)
2) Smartwatch (KT)
3) Emergency response health condition monitoring device (CERTH/HRT)
4) Radiation sensors (wearable)
5) Chemical sensors - Rescue MIMS (NTUA)
6) Drones (UHasselt)
7) Collaborative drones' platform (UHasselt)
8) Rescue Robots & Autonomous vehicles (DFKI)
9) Obstacle Detection System (THALIT)
10) Volunteer application (CERTH)

The representatives of Hellenic National Defense general staff will be invited, they give to S&R consortium the place where the UC4 be held and the Local stakeholders (Regional governor, Mayor, Fire department and civil protection authorities) will possibly attend the pilot as observers. However, the level of their involvement is dependent on their availability at the time of the pilot and their willingness to participate.

3.3 Selected Components introduction

The following paragraphs have the scope to introduce the single selected components provided by the four Partners DFKI (Robot Platform), NTUA (MIMS Box), THALIT (Obstacle Detection Software) and UHASSELT (Drone).

3.3.1 Robot overview

The planned robot platform to be used in this S&R project is the DFKI version of the SeekurJr. It is a very robust outdoor system which can especially be used on uneven, e.g. rocky or sandy ground, or urban environments. On heavy terrain it may struggle due to the low ground clearance. It also is not fully waterproof in the current state, so rain, wet roads and muddy terrain should generally be avoided. Originally, the system is used for the primary research tasks of autonomous self-evaluation and the detection of unspecified failures and disturbances.

The rover is originally equipped with a SICK LMS-111 LiDaR scanner for long range mapping, and extended by a sensor tower at the front, which holds a periodically tilting Hokuyo UTM-30LX-EW LiDaR scanner for close proximity obstacle detection at an extended height, plus a pan-tilt unit with a mounted Velodyne VLP-16 LiDaR scanner and two IDS UI-5240CP Rev 2 GigE cameras for more dynamic perception capabilities including stereo vision. The peripheral components are connected via two switches using Gigabit-Ethernet or USB.
To be able to turn on the spot, the robot is skid-steered by two motors - one on each side. It has a swing radius of 52cm, a maximum linear velocity of 1.2m/s and a maximum traversable grade of 75%.

The rover can run for 2-3 hours on average until the batteries are depleted. This value depends on the rover's tasks and loads. For an extended operation duration, the batteries can be hot swapped manually during a mission, if the white cover on the robot base remains freely accessible. The battery provides regulated power of 2A at 5V, 2A at 12V, and 1A at 24V. It also provides 20A of unregulated power at a nominal voltage of 24V which will be used for powering the ODS.

For autonomy and perception, the robot includes three PCs. Besides navigation and plan execution, the semi-autonomous control particularly includes the prediction of sensor values (generation of expectations) and the self-evaluation (detection of unexpected or unknown situations).

The robot has four easy to access full stop buttons in case of emergency, which halt the entire operation of the robot. In Figure 9, the modified platform is shown in its current state.

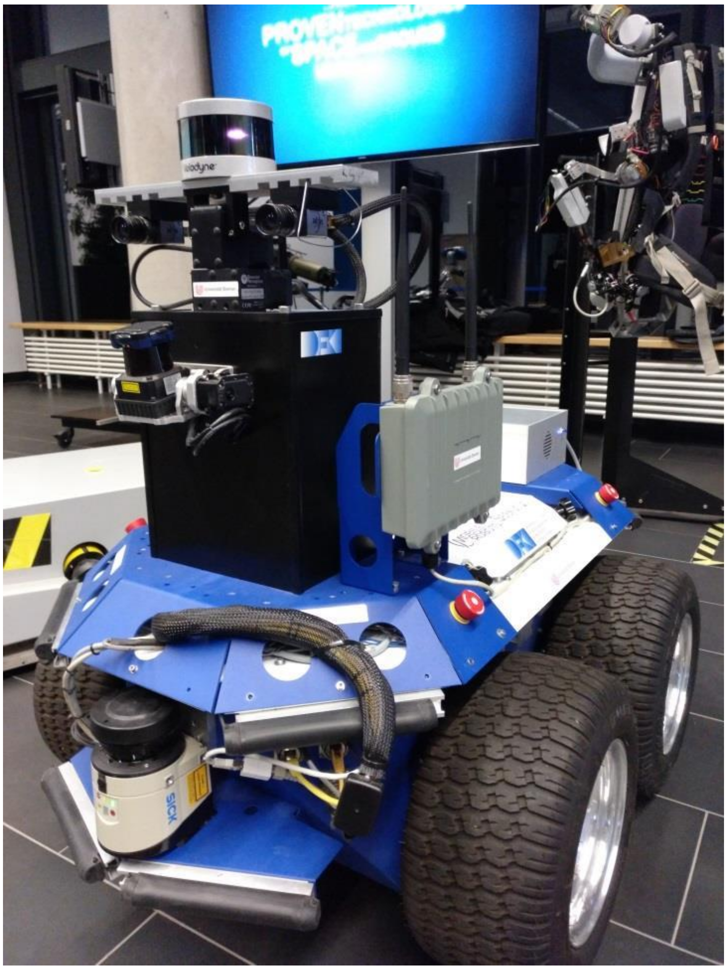
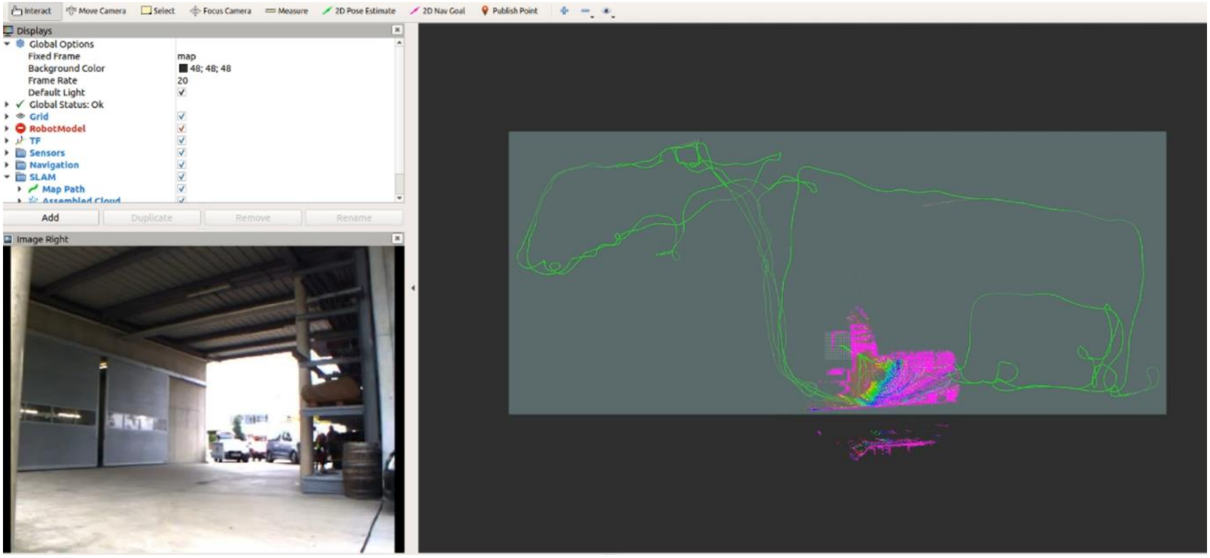


Figure 9: DFKI SeekurJr robot platform

The operation will support manual control and an autonomous exploration mode, which is developed in context of this SnR project. During the operation, the robot generates a spatial map to assist first responders in getting a map overview.

3.3.1.1 Localization and Mapping

Since spatial mapping requires the accurate localization of the robot and vice-versa, the problem of Localization and Mapping for a Robot System is usually referred as *Simultaneous Localization and Mapping (SLaM)*. Both tasks are fairly important in SnR to gain a broad overview of the environment for first responders. For SLaM we use RTABMAP [15], which recently combined various approaches and achieved the State-of-the-Art in performance. The odometry is calculated with frame-to-frame ICP matching (with an aggregated pointcloud spanning a few scans and wheel odometry as initial guess) and the loops are closed based on ORB-features from the camera images and consecutive ICP matching. Figure 10 hereby shows a sample trajectory across the firefighting academy in Tulln from UC3.



Global Options
Fixed Frame map
Background Color 48; 48; 48
Frame Rate 20
Default Light ✓
Global Status: Ok
Grid ✓
RobotModel ✓
TF ✓
Sensors ✓
Navigation ✓
SLAM ✓
Map Path ✓
Assembled Cloud ✓

Figure **10**: Sample Robot Trajectory

The spatial mapping is done by insering the laserscans from the Velodyne VLP-16 into an Octomap [16], which voxelizes the point clouds into hierarchical blocks of varying size. An example output of the produced voxel map is shown in Figure 11, where the color visualizes the height of each voxel.

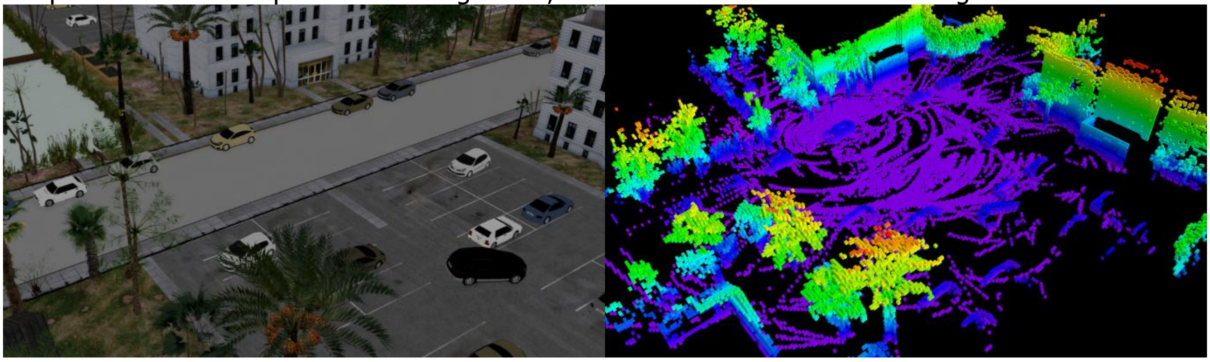


Figure **11**: Spatial Voxel Map in Simulation

We chose a voxel size of 0.25m, as it is able to represent most structures and larger objects like cars. To be able to distinguish much smaller objects, the voxel size would have to be significantly lower, which in turn would greatly increase the required memory for the map, especially on larger operational areas. In case of detected loops in the robot trajectory, the buffered pointclouds, which are sampled at significant motion differences (>2m), are reprojected into the map from the updated locations to rebuild the spatial map.

3.3.1.2 Simulation

To test a robot’s operation, a simulation is a useful tool. It can also be used to generate data for machine learning algorithms to train neural networks for 3D object detection with self-supervised learning [17] and autonomous exploration with reinforcement learning [18].

To simulate SnR environments, in particular earthquakes, we create randomized building using procedural generation by iterative optimization of floorplans, which are then extruded to 3D building components. The buildings are then randomly collapsed using the Blast physics environment in Isaac Sim, which splits the building into rubble parts with a Voronoi algorithm. We apply simulated earthquake forces at the ground level to then break the binds between the parts and make them fall. One possible result of this operation is shown in Figure 12: with the simulated robot in the bottom left corner.

Figure **12**: Collapsed building structure in simulation

In that particular example we added fire as a visualization and a background rendering. Those are currently not used, as neither the mapping nor the autonomous exploration makes use of Camera data. But they can be easily integrated in the future. One possible extension would be adding Humans as shown in the Figure and getting them possibly trapped under rubble, so the robot can be trained to explicitly search for vixtims.

3.3.1.3 Obstacle Avoidance

As a safety measure we added an obstacle avoidance layer, to prevent the system from running into obstacles unseen by the camera (steps or drops). This layer would act as an additional safeguard to stop the robot in case of immediate danger. This obstacle avoidance uses the Hokuyo LiDaR at the front of the tower angled at fixed 50° towards the ground.
The projected points from the LiDaR are then checked against the ground level of the robot to measure the incline the robot is currently going on. The more the highest absolute distance in z-direction deviates from the ground level, the more the robot is slowed down. It comes to a full stop at an elevation difference of 0.2m, which prevents it from going up or falling down stairs.
The obstacle avoidance also takes obstacle positions and velocities from the ODS and measures collisions with a lookahead of 2s. It stops, if an object were to collide within that timeframe. Upon stopping the robot is only able to move backwards or rotate around its vertical axis.

3.3.1.4 Manual Control

The robot can be directly controlled without any software with a control stick as shown in Figure 13:. This allows the operation of the robot despite software malfunction, but it requires the operator to be directly connected to the robot.

Figure **13**: SeekurJr direct control stick

For the remote control of the robot by the operator, we used an off-the-shelf gamepad (Logitech F510), as shown in Figure 14:. We used the same wireless network connection as for the remote inspection of the sensor data for the transmission of the control signal. This way, the remote operator can control the system from a safe distance.

Figure **14**: Logitech F510 for manual control

For the remote control the operator needs to press and hold a button (L1) to enable control while simultaneously using the steering stick (right analog stick) for providing the actual control command in terms of linear and angular velocity. The command signal is then sent continuously from the remote operator computer to the obstacle avoidance layer running locally on the robot. This layer would then stop the robot once it detects the last received control command is older than the configured age threshold. It would also automatically stop the robot when the sensor data indicates a large enough step or drop in front of the robot. By pressing and holding another button (R2), the robot uses the maximum available velocity of up to 1.5m/s, which is recommended for open field operation.Another control input was integrated in the obstacle avoidance layer, to support safe autonomous exploration control. Here too, the operator would be required to press a designated enable button to allow the control commands to be forwarded to the base rover. This allows immediate stopping of the autonomous operation, in case the robot does something unexpected or dangerous, or loses the connection to the controller.

3.3.1.5 Autonomous Control

For the autonomous operation we use a Reinforcement Learning agent, which is trained on the simulation. We use the Soft-Actor-Critic (SAC) [19] algorithm for this task, as it has been proven to be very sample efficient and easily parallelizable through a replay buffer. The architecture is displayed in Figure 15. A set of sampling agents run the simulation with the following steps:

1. Update the neural network to the most current trained state.
2. Pick a random pre-generated scene with buildings, cars, objects, people, etc. and insert it into Isaac Sim.
3. Generate a random building structure as described in 3.3.1.2 and replace a building from the scene with that building.
4. Collapse the building with BLAST with a random amount of blocks and generated Earthquake forces, which are strong enough to separate the blocks.
5. Generate a randomized bounding box broadly around the replaced building as exploration goal. The robot gets rewarded for every explored voxel inside that bounding box.
6. Place the robot close to that area and let it explore the area with the predicted actions from the neural network for a fixed amount of steps at around 10Hz.
7. Store the transitions in the replay buffer including the current state, performed action, next state and reward for the performed action.

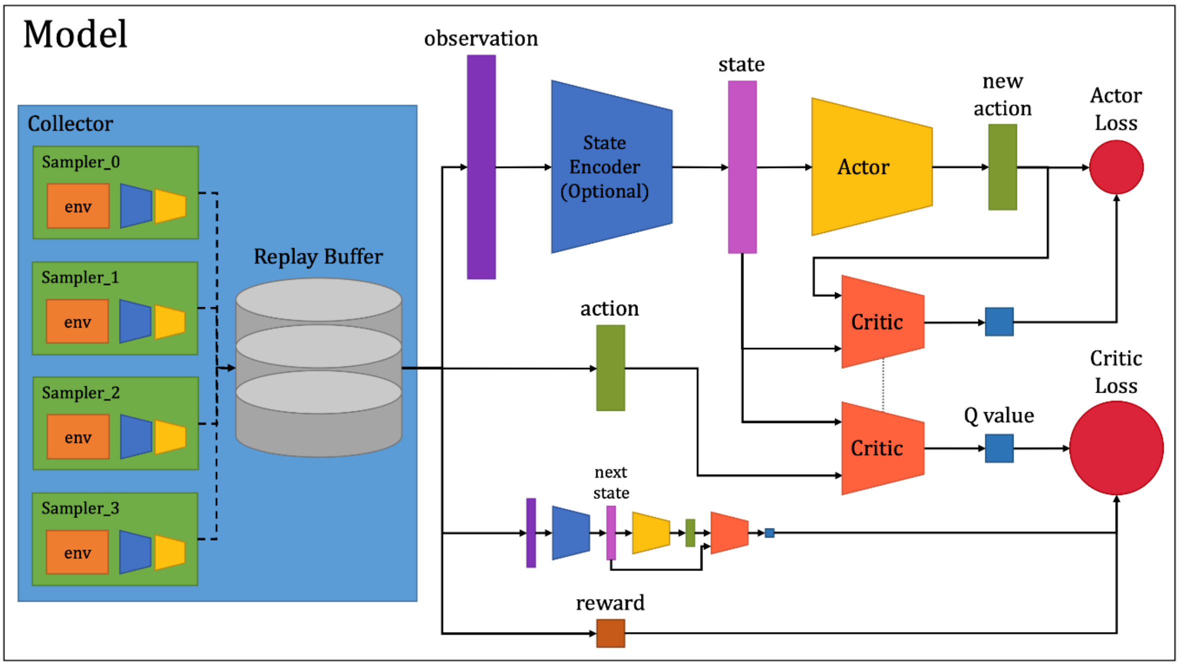


Figure **15**: Soft Actor-Critic architecture

The training stack then can pick data from the replay buffer and train the network on that data as shown in Figure 15 and periodically store it, so the samplers can load it in the first step.
For actor and critic we use simple Multi-Layer_Perceptrons. To encode the Voxelmap state we use the Minkowski Engine [20] with 6 Residual Convolutional Blocks with 2 layers each. The 8 bounding box corners of the exploration goal are injected directly into the state embedding before it is fed into the actor and critic networks.
The agent is trained with this method until it reaches satisfying exploration outputs. Due to the complexity of the network, this method does not always converge and requires fine hyperparameter tuning, preferably on empty space without any building or objects.

This approach can further be extended to search explicitly for victims under rubble by adjusting the reward function to only add up the voxels, which represent such a Human.

3.3.2 MIMS overview

The RESCUE-MIMS device that will be delivered in S&R project is a prototype of technology readiness level (TRL) 6 that has been designed and developed in the prospect of satisfying the majority of the end-users' requirements that have been indicated inside D1.2.

Figure 16. The rescue-MIMS chemical device

RESCUE-MIMS device can be used for the early detection of toxic environments for the first responders in terms of hazardous VOCs or semi-VOCs identified in the disaster environment. Membrane inlet mass spectrometry (MIMS) can generally offer high sensitivity (from low parts per billion-ppb, to low parts per trillion-ppt), fast and accurate analysis, minimizing false alarms and sample preparation requirements. It can be used for both single and multicomponent mixtures. Since it is a field instrument, it can be used either as a handheld device, or as a payload, on-board robotic platforms. It can be used as a stand-alone device coupled with a power bank; the power bank that has been tested in the field under 'UC5-People trapped under rubbles' provided with power autonomy of 2,5- 3 hours but it can be extended, depending on the power bank's capacity.

3.3.3 Obstacle Detection System overview

In the context of S&R Project the Obstacle Detection System is a Prototype developed within the T3.4, for the detailed description refer to the D3.6. In the T5.4 ODS has been integrated in the Robot Platform, with the main objectives as following:

- Detect and track obstacles, fusing information coming from different technologies of sensors;

- Notify detected objects to the robot. The robot uses this notification to stop itself in case of a potential collision;
- Make the robot's pilot aware of the surrounding environment and notify him/her of obstacles detected;
- Cover different scenarios despite weather conditions and unavailable sensors.

Consequently, ODS main functions are:

- Acquire sensors (LiDAR and Camera) raw data;
- Filter and process raw data at sensors outputs;
- Detect obstacles in front of the robot, associating information from different sensors and tracking them.

The ODS block diagram is represented in Figure 17. The ODS system includes two different sensors (LiDAR, stereo camera), whose data are fused together in order to improve obstacles detection probability. Moreover, the use of multiple sensors allows to improve the detection in different environments in which certain sensors perform better than the others. As an example, in nightly scenarios, a LiDAR sensor can be used to detect objects with more accuracy with respect to a non-infrared camera.

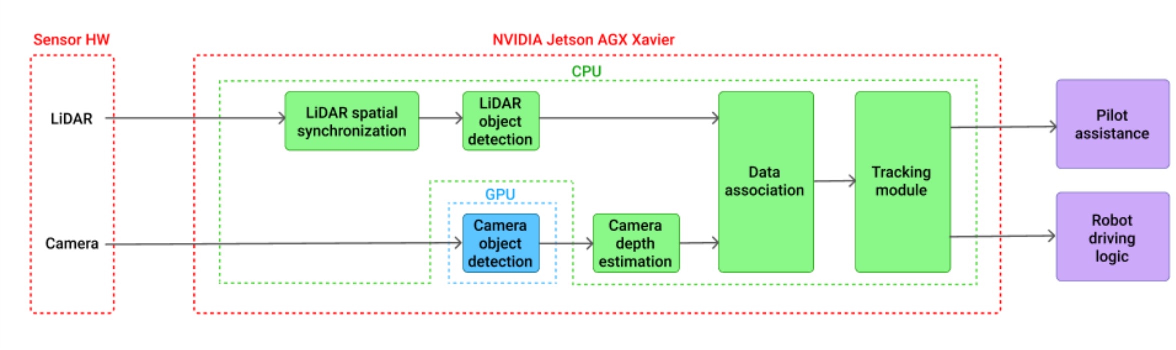


Figure 17: ODS block diagram

Inputs of the system are smart sensors: each block is composed by the hardware device and a sensor driver that is in charge of receiving the data in form of ROS messages and forwarding it to the following blocks.
Output of sensors can be processed by a spatial synchronization module, which is responsible for applying roto-translations to input data or to represent the information in the same reference systems.
Then objects are detected on sensors raw data. So:

- Clustering algorithm were implemented, to aggregate LiDAR 3D point cloud.
- Convolutional Neural Network (CNN) is used on video frames, enclosing objects detected by the model in Bounding Boxes (BBs).

Later, depth estimation module represents BB information (like central point coordinates, width, and length) on the robot Cartesian coordinate reference system. At the end of this process, objects detected by LiDAR and camera are represented in the same reference system and they can be compared.
The Sensor Fusion algorithm is a fundamental and crucial stage of the ODS composed by two steps: data association and tracking. They analyze one time step the given data and decide on the most likely measurement-to-track associations. Objects detected coming from different sensors are associated using the Global Nearest Neighbor (GNN) algorithm. In order to increase the methods

robustness, some constrained extra information can be added, e.g.: speed, obstacle width and/or length, etc.
A limited number of the associated objects can be tracked with Linear Kalman Filters (LKFs) or Unscented Kalman Filters (UKFs).
Finally, the Collision Checker Module evaluates if detected objects located in the Region of Interest (ROI) could be obstacles for the robot and sends the alarm to the pilot. ROI for the collision warning has a defined length and width.
The output information of the ODS for the robot are the following:

- Reference time of detected objects;
- Objects position (x, y, z) ;
- Objects speed;
- Measure of uncertainty of the given data;
- Objects class, which belongs to the set <Pedestrian, Car, Dogs>.

Moreover, the system provides a web application that allows to visualize the processing data of the ODS. In particular, it provides MJPEG stream by aggregating raw images from stereo camera, bounding boxes detected from CNN. Moreover, it provides the visualization of the 3D environment by using LiDAR data, enriched with information about the tracked objects. This data can be viewed in the operator's console to assist the operator in his/her tasks.
ODS runs in the NVIDIA Jetson AGX Xavier board composed by:

- CPU: 8-core ARM v8.2 (x64) @2.26 GHz, 8MB L2 + 4MB L3;
- GPU: 512-core Volta GPU @ 1.37 GHz with Tensor Cores;
- RAM: 32GB 256-Bit LPDDR4x (137 GBps).

The OS installed in the NVIDIA Jetson AGX Xavier is a Linux-based, in order to support the Robot Operating System (ROS).
The following figure shows the NVIDIA Jetson AGX Xavier and the related Peli Protector 1400 box that contains it:

Figure 18: NVIDIA Jetson AGX Xavier

Figure 19: Peli Protector 1400 box

ODS prototype presents the following interfaces:

1. Metallic circular connector for the power supply at 24 V.
2. 2 x female Ethernet connector: one for the connection with the robot and the other for debug;
3. Green LED. When the ODS prototype is fed, the green LED in ON.

3.3.4 Drone overview

The Drone that was provided is DJI phantom 4 Pro v2. This drone weight 1375g with the battery and propellers. It can fly for around 30min using a 6000mAh LiPo 2S battery. The drone has three speed modes (S-mode: 45 mph (72 kph); A-mode: 36 mph (58 kph); P-mode: 31 mph (50 kph)) and has an approximative max wind speed resistance of 10m/s. The DJI phantom 4 Pro v2 can operate in temperature range from 32° to 104°F (0° to 40°C) and support two satellite positioning system (GPS/GLONASS).

Figure 20: Dimension of DJI Phantom 4 Pro v2.0

The provided drone includes a camera onboard with a Gimbal of 3 axes for stabilization (pitch, roll, yaw). The Gimbal pitch could be controlled from -90° to +30° with a max speed of 90°/s.
The obstacle avoidance system of the drone with the Gimbal provides three Field of View (FOV). A forward and backward view with a variation degree of 60° (Horizontal) and ±27° (Vertical). A downward view with a variation degree of 70° (Front and Rear) and 50° (Left and Right). The vision system has an Obstacle Sensory Range of 2-98 ft (0.7-30 m).
The DJI phantom 4 Pro v2 has also an Infrared Sensing System with a FOV of 70° (Horizontal), ±10° (Vertical) and obstacle sensory range of 0.6-23 feet (0.2-7 m).
The camera integrated with the Drone provide a FOV of 84° 8.8 mm/24 mm (35 mm format equivalent). It provides pictures with three aspect ratios (3:2 Aspect Ratio: 5472×3648, 4:3 Aspect Ratio: 4864×3648, 16:9 Aspect Ratio: 5472×3078) and support different photography mode like Single Shot, Burst Shooting, Auto Exposure Bracketing (AEB) and Interval. The images could be saved in different formats (JPEG, DNG (RAW), JPEG + DNG)). The camera also supports different Video Recording Modes including Cinema 4K (C4K: 4096×2160 24/25/30p @100Mbps) and different video formats (MP4/MOV (AVC/H.264; HEVC/H.265)). The video could be saved in the microSD of the drone which has a capacity of 128GB or live streamed to live stream platform like Facebook, Youtube, WeiBo or a customized (hosted or local) RTMP (Real-Time Messaging Protocol) server with a max live view quality of 1080P.

4 Robot System Integration

4.1 Functional requirements

To provide first responders with crucial information of the environment in form of spatial maps and gas measurements, the robot needs a proper network interface as well as hardware interface to mount the necessary tools for the job. This includes a) a 4G/WiFi router, b) the RESCUE-MIMS system case, c) the Obstacle Detection System (ODS), d) an additional voltage regulator to provide power to the ODS, and e) an ethernet hub to connect these components, so they can access the network independently as well as work as a unit for controlling the robot. The sensors of the robot need to provide the data to the Obstacle Detection System, which then provides obstacle information to the robot for semi-autonomous control as well as to the driver on the control room for manual control, in case the semi-autonomous system fails or does not lead to desired robot operation.
Ideally, the white battery cover of the robot should remain accessible after mounting all components, so the batteries can be hot-swapped during an operation.

4.1.1 Robot Functional Requirements

In this section the Functional Requirements of the Robot system are listed:

1. The Robot shall provide a hardware interface (like metal brackets) to mount all the additional components.
2. The Robot shall provide the proper Power to the components that requires it (ODS).
3. The Robot shall provide a dedicated internal network where all networking components are linked via Ethernet and connect to a remote-control station via WiFi.
4. The Robot shall navigate with a driver or in semi-autonomous mode with a 3D-Exploration Algorithm.
5. The Robot shall Integrate the Obstacle Detection System in order to elaborate the output of the Detection SW and to decelerate/stop the movement, in particular the ODS will provide information to the onboard Robot System by outputting fused obstacles position and speed data in the robot reference system. Moreover, the ODS output will be available on a ROS topic whose content describes objects position and Speed.

4.1.2 ODS Functional Requirements

In this section the Functional Requirements of the Obstacle Detection system are listed:

1. ODS system shall run in the NVIDIA Jetson AGX Xavier Developer Kit.
2. ODS interface with the robot shall be the RJ45 Ethernet port.
3. The ODS shall detect and distinguish the following objects categories:
    a. Pedestrian;
    b. Car;

   c. Dogs.
4. ODS system shall have an input power of 24 VDC nominal (18 VDC – 36 VDC), which is power supply of the HW prototype.
5. The HW/SW platform shall support ROS framework to transfer ROS messages between components.
6. The Sensor Fusion Algorithm shall be executed in the CPU of the AGX Xavier board.
7. The object detection SW module on camera frames shall run in the GPU of the AGX Xavier board.

In order to instruct the Algorithm of ODS, some video coming from End-user has been used to test the good results of the performance.

4.1.3 MIMS Box Functional Requirements

In this section the Functional Requirements of the MIMS Box are listed:

1. The MIMS Box shall detect the chemical hazards for the safety of the first responders; the Chemical device will be installed on the Robot Platform for remote sensing.
2. The MIMS Box shall be powered by the MIMS battery (power bank luggage).
3. The MIMS Box shall communicate the Chemical data to the Control room via COncORDE platform. Based on D5.3 outcomes, Benzene, as well as Carbon Monoxide and/or Carbon Dioxide can be selected as key compounds for on-line monitoring in the pilot demonstration of UC4. More details are provided in D5.7.

4.2 System architecture

The system setup of the robot is shown in Figure 21. All hardware components need to be mounted on the robot platform. While the sensors are already mounted, the RESCUE-MIMS, 4G Router, Ethernet Hub and ODS have to be mounted additionally. All components can then individually communicate with the control room over the router through an Ethernet hub.
The Control Room is where the user is located to supervise the Robot operations.

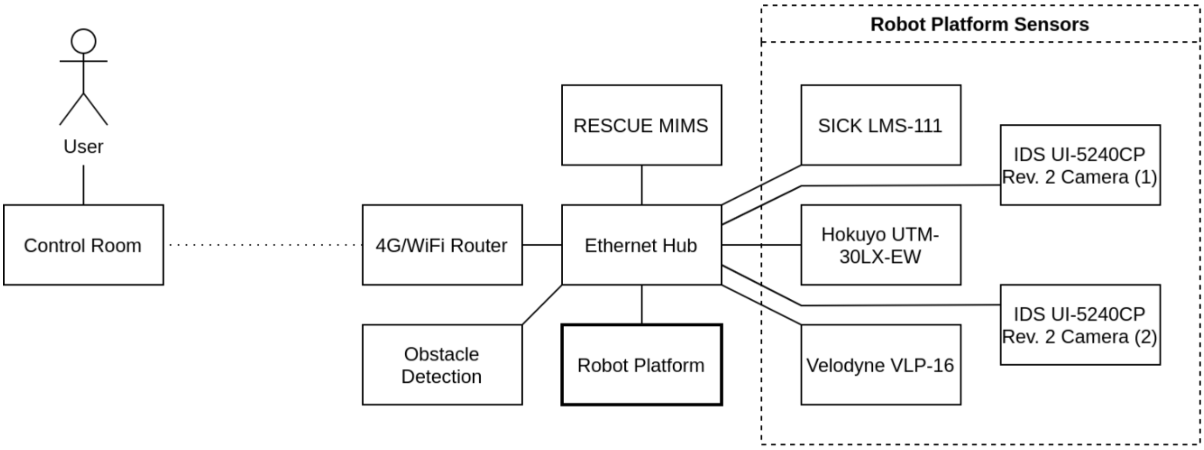


Figure 21: Robot Platform System architecture

4.3 Hardware architecture

4.3.1 Hardware architecture of the Robot Platform

As already introduced, the planned robot platform to be used in this S&R project is the SeekurJr. The rover is originally equipped with with a SICK LMS-111 LiDaR scanner for long range mapping, and extended by a sensor tower at the front, which holds a periodically tilting Hokuyo UTM-30LX-EW LiDaR scanner for close proximity obstacle detection at an extended height, plus a pan-tilt unit with a mounted Velodyne VLP-16 LiDaR scanner and two IDS UI-5240CP Rev 2 GigE cameras for more dynamic perception capabilities including stereo vision. The peripheral components are connected via two switches using Gigabit-Ethernet or USB.

To be able to turn on the spot, the robot is skid-steered by two motors - one on each side. It has a swing radius of 52cm, a maximum linear velocity of 1.2m/s and a maximum traversable grade of 75%.

The rover can run actively for 3 on average until the 3 batteries are depleted. For an extended operation duration, the batteries can be hot swapped manually during a mission, as long as the white cover on the robot base remains freely accessible. The battery provides regulated power of 2A at 5V, 2A at 12V, and 1A at 24V. It also provides 20A of unregulated power at a nominal voltage of 24V.

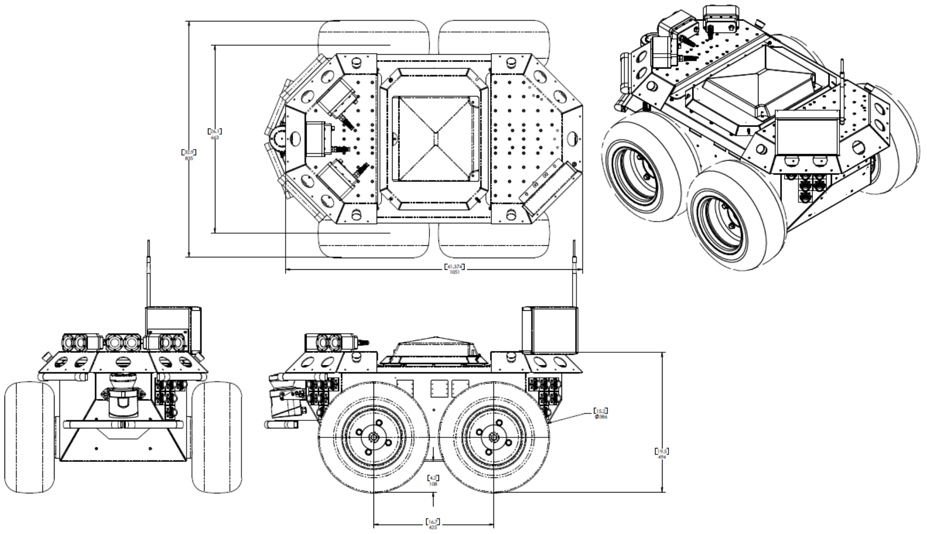


Figure 22: Robot Platform Hardware architecture (basis System w/o DFKI extensions)

4.3.2 Hardware architecture of the MIMS Box

The Rescue MIMS prototype comes in a configuration of a hand-held peli-box luggage about 60x50x20 cm that encloses the inner parts of the mass analyzer, in order to be robust and withstand the harsh operational environment; straps can potentially be integrated to be used as back-back equipment. The Rescue MIMS luggage can be connected with a portable PC or tablet e.g. 9″-10″ or bigger, where the results of the measurements will be displayed (monitor display). In Figure 5, the 3-D graphic of the RESCUE-MIMS device is provided. More details on the prototype TRL 6 that will be delivered inside S&R, as well as proposals for optimization in a future version of TRL7-9 are available in D5.1, M10.

Figure 23: RESCUE-MIMS device: hand-held robust peli-box luggage

The RESCUE-MIMS can also be mounted on fire-fighters vehicles (roving system) or tested as a payload on robotic platforms in order to serve as a screening tool for early warning. This configuration can protect first responders as well as canines from exposure to toxic environments.

The RESCUE-MIMS prototype is foreseen to be installed on-board DFKI ground robot SeekurJr refer to the following Figure 24, more details are provided in D5.1.

Figure 24: RESCUE-MIMS on-board DFKI robotic platform SeekurJr

4.3.3 Hardware architecture of the ODS prototype

The ODS prototype is composed by the Peli 1400EU Protector Case including the Xavier board and a 60Watt DC-DC convert from 24 V to 12 V, refer to the following figure:

Figure 25: ODS 60Watt DC-DC convert

The dimensions of the ODS HW prototype are presented in Figure 26 together with the three interfaces. Reading Figure 11 from left to right, the following connectors are illustrated:

- RJ45 interface, for the Ethernet connection between the Xavier board and the robot.
- Power supply interface, which is a circular 3 pins connector.
- Green LED, which is turned on when the ODS HW prototype is fed.

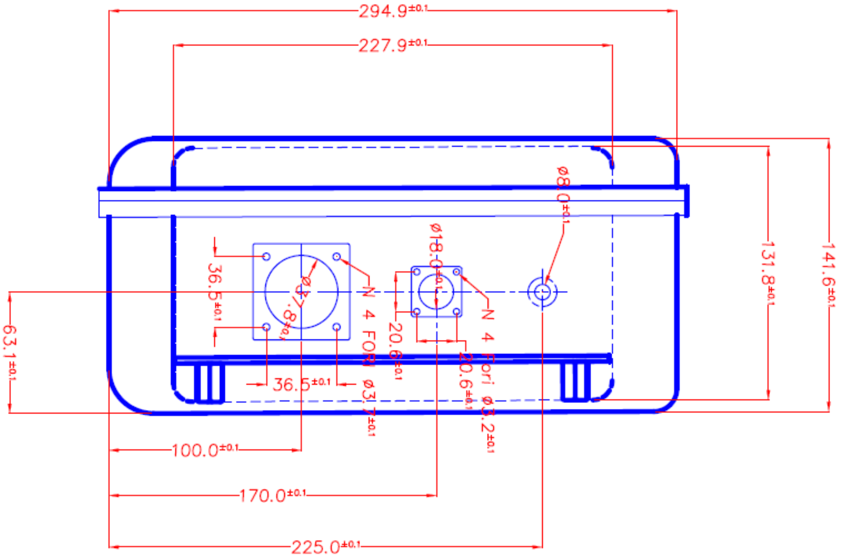


Figure 26: ODS Design of the interfaces of the HW prototype

4.4 Communication interfaces

The robot, the ODS, as well as the control room will communicate via ROS (noetic), which is a networking middleware to allow communication between the single components. Hereby, the sensor data will be provided by the robot in form of sensor_msgs/Image and sensor_msgs/PointCloud2 messages for the camera and LiDaR data respectively, where the camera data will be sent to the control room for observation, to the ODS for obstacle detection, and to the robot for mapping, while the LiDaR data will only be sent to the robot platform for the mapping, and to the ODS for the obstacle detection. The control room will be able to send control commands for manual operation and a map section for semi-autonomous exploration. The robot platform will use the sensor data to generate the spatial map and send it to the control room. The gas measurements can then be inserted into the map at the control room or robot directly, depending on where the respective ROS node will run. The obstacle information will be provided by the ODS with a custom message format to the robot. These messages will then be used by the robot and control room to control the robot manually and (semi-)autonomous exploration.

The communication layout is displayed in Figure 27.

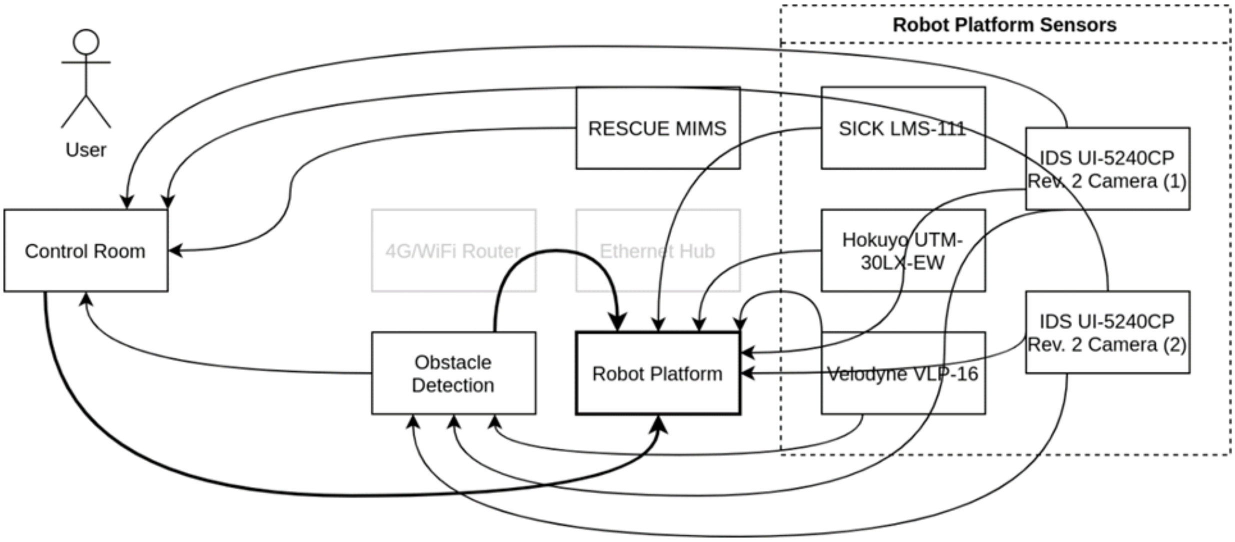


Figure 27: Communication interfaces in the Robot Platform

5 Drone System Integration

5.1 Functional requirements

The drone will mainly fly and provide video stream which could be transmitted to a steaming server from the remote-control unit or from the laptop. The streaming server will provide the video input for the video analysis module via a 4G or Wifi communication. The video could be provided from a max altitude of 120m meters following the EU Regulation (2019/947) and with a max quality of 1080P. The best quality of video is provided by the wired connection. The drone flight could last for max 25 min. The drone will also provide data about the level of its battery, the camera position and the drone GPS position. To perform these tasks, the drone must have a full charged battery and should be operated by a certified drone pilot. The main important scope of the Drone is to give an overall view of the S&R environment to the Robot driver in order to avoid dangerous area like fire zones.

5.1.1 Drone Functional requirements

In this section the Functional Requirements of the Drone system are listed:

1. The Drone shall fly next to the Robot Platform in order to have a top overview of the related environment
2. The Drone shall provide video stream which could be transmitted to the driver of the robot in order to support on the Rescue operations.
3. The drone flight shall last for max 25 min.
4. The drone shall provide data about the level of its battery, the camera position and the drone GPS position.
5. The drone shall be operated by a certified drone pilot.

5.2 System architecture

The DJI phantom 4 pro will be controlled using the remote control in which a tablet or phone could be connected via a wired connection. The tabled or phone will be setup up with a 4G connection and the DJI GO 4 mobile application will be installed in this device. This application could be setup up to stream video to a RTMP server. The video stream could also be displayed in the Windows application installed in the laptop and then the video could be streamed from the laptop to the streaming server using 4G communication.

5.3 Drone HW Architecture

The data from the drone will be communicated to the DJI Go 4 application. This application could transmit the video stream directly to the streaming server via 4G communication. Also, it is possible to collect the live video view from the windows application and stream the video view from the laptop to a streaming server via a 4G communication. The other data (GPS position, battery level, camera position) will be transmitted to a laptop via a wired communication. The laptop will then send the data to provide the required information to the MQTT Broker. The data from the MQTT Broker will be then collected as Kafka messages in the Data Lake via a DJI SDK based application.
The following Figure shows the Drone Communication Architecture:

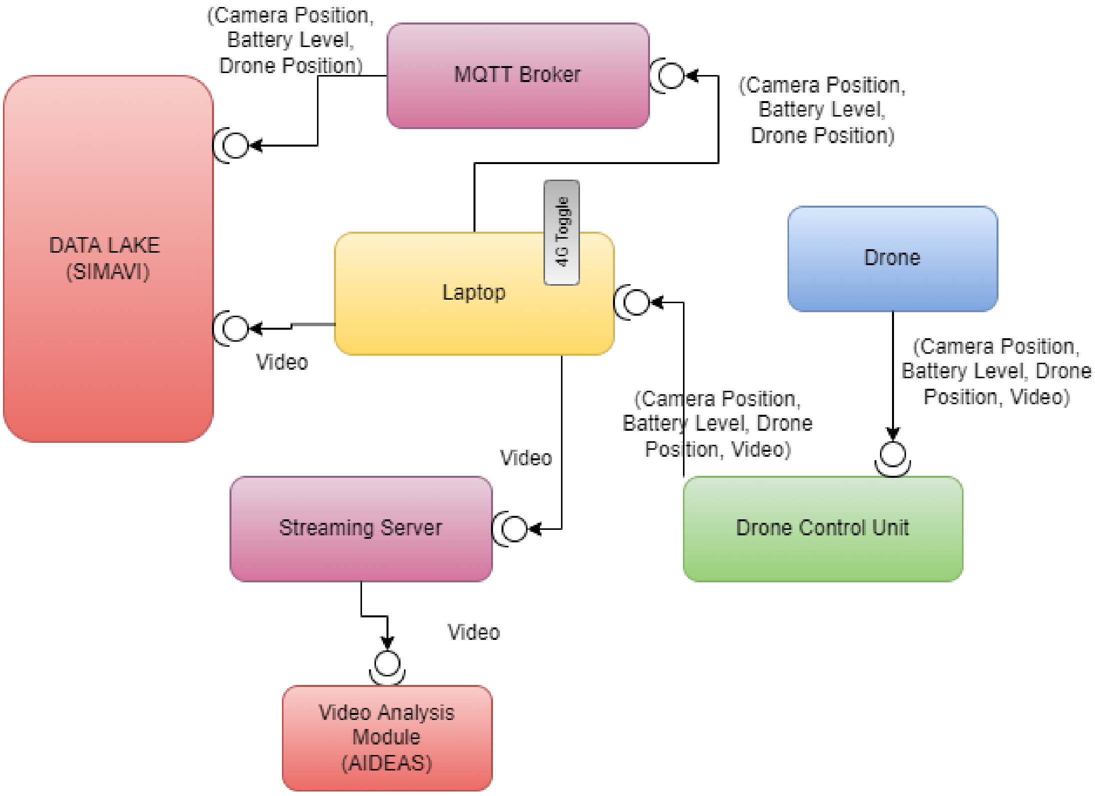


Figure 28: Drone Communication Architecture

5.4 Communication interfaces

The drone will send the video and the data to the drone control unit via the OcuSync 2.0 Transmission System. The DJI Go 4 application will be installed on a tablet, a smartphone or a build-in screen of the remote connected to remote control. The Tablet is equipped with a 4G or Wifi communication. The collected video stream will then be transmitted from the tablet to a streaming server via 4G or Wifi connection. The video view could also be visualized from the DJI SDK Windows application over a wired connection. The streamed video could be then retrieved by the video analysis module using Wifi or 4G communication. The DJI SDK based windows application will also transmit the data of the drone including the battery, the GPS location and the position of the camera to the Data Lake via the MQTT Broker.

The following Figure shows the Communication interfaces for Drone video stream and data:

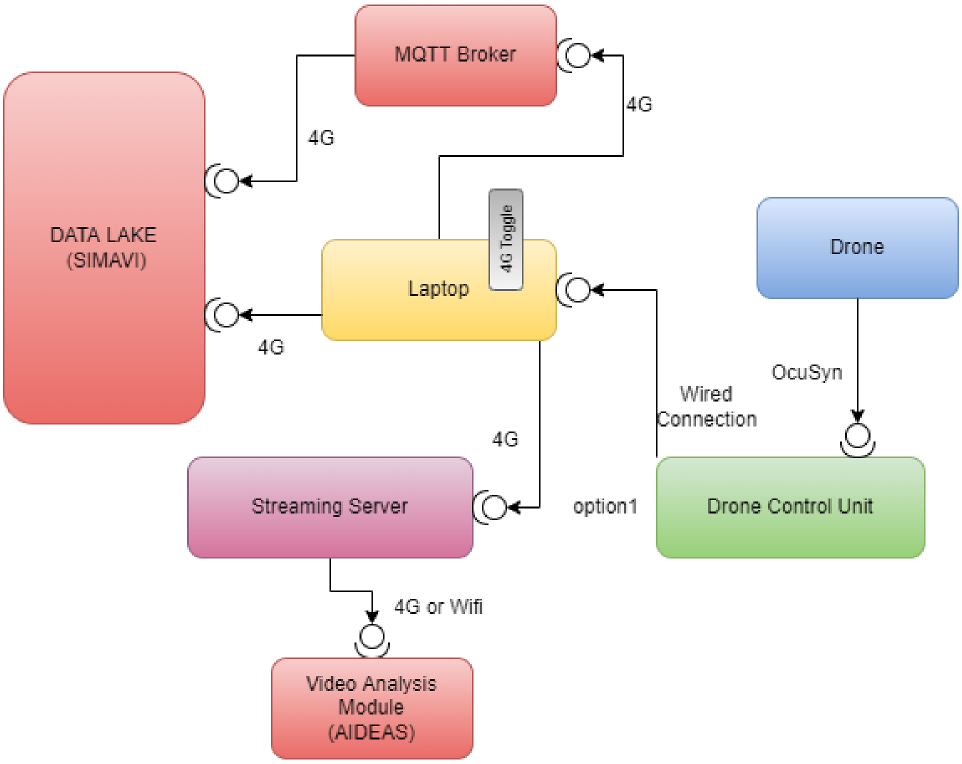


Figure 29: Communication interfaces for Drone video stream and data

6 Stand-alone Pretesting

Following the integration and testing strategy described in the paragraph 2.3, hereafter are listed all the stand-alone tests performed on the single components both from HW and SW point of view.

6.1 Hardware tests preparation

6.1.1 Robot HW tests preparation

Prior to testing the integration of all components on the robot, the robot will be tested with a sample payload which roughly represents the final one. This is done to avoid later complications with mounting the hardware components. To achieve this, a PeliCase of the model, which is also used for RESCUE MIMS, will be filled with weight to represent to load of the sensor box and mounted using a planned hole pattern on the robot. With this payload, the robot will then be moved around outdoors to test the motion capabilities. Since the other components already have fixed mounting patterns, they will be omitted in this test.

It also has to be tested, that all sensor data provide correct data with covariance information. For this, all sensors have to be calibrated before testing.

6.1.2 MIMS box HW tests preparation

NTUA who will provide the RESCUE-MIMS chemical device will organize and run several laboratory experiments for testing various factors regarding the performance of the device, so that to scale up its use in the field under the UC4 pilot demonstration.

Specifically, a number of different chemical compounds and their mixtures have been prepared in different concentrations and combinations in order to test response times and other analytical characteristics of the has been set including the method of the analysis that will also be used in the field, e.g. the specific masses to be monitored, the cycles of scans, etc. The RESCUE-MIMS system was evaluated by addressing the following analytical criteria: (a) response times (b) linear dynamic range within the examined concentration area, (c) sensitivity (LODs), (d) repeatability. Specifically, RESCUE-MIMS was tested and validated in lab-scale with chlorinated compounds since they are considered potentially hazardous product in case of industrial accidents and because the RESCUE-MIMS will be demonstrated in such a fire industrial incident scenario under UC4. For the same reason, Benzene was also used for testing because it is one of the core compounds of BTX (Benzene, Toluene, Xylene) that is mainly evolved in forest fires and/or industrial fires. Additionally, for the situation awareness and the alarms triggering during the trial, other compounds can also be measured like Carbon Monoxide and/or Carbon Dioxide. Detailed description of the experiments is provided in D5.3.

6.1.3 ODS HW tests preparation

At first tests of the ODS HW prototype were executed in the laboratory. Using the multimeter, a check of the electric connections within the HW prototype was required. Then, the power supply was set to 24 V and it was switched off. The two cables were connected to the ODS HW prototype:

1. Power supply;
2. Ethernet, in order to connect a laptop and verify the publication of ROS messages.

The laboratory test setup of the ODS HW prototype is represented in Figure 30.

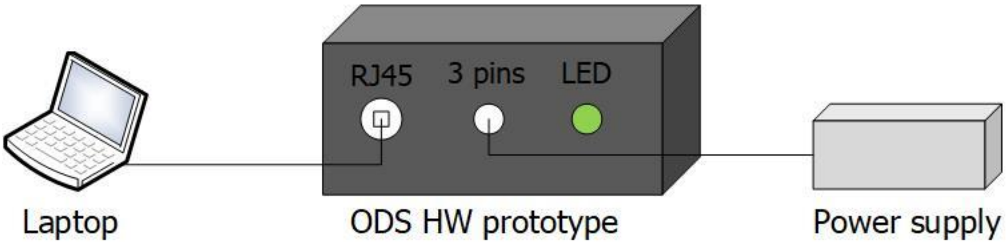


Figure 30: Setup of the tests in laboratory

Switching on the power supply, if these HW tests were completed successfully (without short circuits and electromagnetic interferences), the ODS HW prototype was ready to go on the field. It communicate with the robot through the RJ45 interface.

6.1.4 Drone HW tests preparation

The following hardware should be prepared and pretested before the Pilot:

- Drone DJI phantom 4 Pro v2 Quadcopter.
- 4k Camera & Gimbal (pre-installed)
- Intelligent Flight Battery.
- Remote Control.
- Battery Charger with the cable.
- USB OTG Cable
- 4G Toggle of connection.
- Micro-USB Cable
- Remote control device: Tablet or Smartphone.
- Laptop with charged battery.
- Streaming Server (Local or Online).

6.2 Software tests preparation

6.2.1 Robot SW preparation

The robot will be first tested in a simulation to make sure the software stack is fully functional with simulated sensor data. That way the amount of integration issues can be minimized.
The simulated scene will contain the robot and a sample environment, which roughly represents a S&R scenario containing a collapsed building and rubble. The robot will be moved on the environment using the manual control and semi-autonomous exploration. This is expected to work sufficiently stable and accurate prior to doing the real integration tests with the actual robot.

6.2.2 MIMS SW preparation

All the SW related to the Chemical device within the MIMS box will be tested in advance respect to the pilot.

Figure 21 presents the mass spectrum of Benzene recorded by the RESCUE-MIMS prototype in lab-scale for different concentrations, by scanning in the mass range of 70 to 85 amu; 12.5 ppm (in navy), 6.25 ppm (in red), 3.13 ppm (in grey), 1.56 (in orange), 0.78 ppm (in light-blue), 0.39 ppm (in green), 0.12 ppm (in dark-blue), 0.06 ppm (in purple). It’s clear that mass 78 recorded is the most abundant.

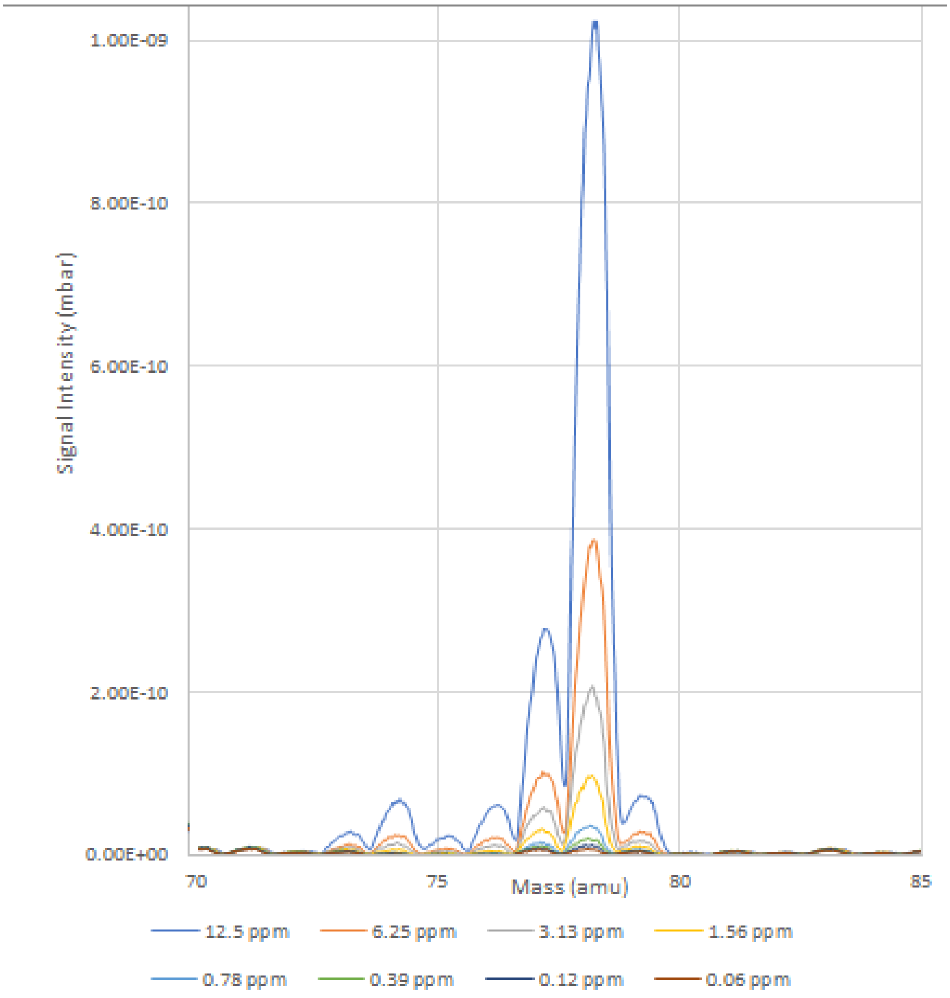


Figure 21 Mass spectra of Benzene recorded for different concentrations in the range of 70 to 85 amu; 12.5 ppm (in navy), 6.25 ppm (in red), 3.13 ppm (in grey), 1.56 (in orange), 0.78 ppm (in light-blue), 0.39 ppm (in green), 0.12 ppm (in dark-blue), 0.06 ppm (in purple)

Detailed description of the lab-scale experiments is provided in D5.3.

6.2.3 ODS SW preparation

All Docker containers had to be switched on. Feeding the ODS HW prototype and connecting the Ethernet cable to the robot, it was possible to check if the defined ROS topics are published and their consistency. The contents of ROS messages were under definition according to the developments of the ODS algorithms. The following preliminary standalone tests were foreseen in the ODS platform before the robot integration:

- Test on Camera ROS driver
- Test on LiDAR ROS driver
- Tests with all Sensors on laboratory host
- Test with all Sensors with Xavier
- Test with all sensors, Xavier and ODS Algorithms

6.2.4 Drone SW preparation

For the test preparation the following software need to be prepared:

- DJI GO 4
- DJI Assistant 2 For Phantom
- Streaming Server Software.
- Encoder Streaming Software.
- DJI SDK based Windows application.

7 Test Descriptions

7.1 Pre-Test considerations

7.1.1 Prerequisite conditions

In general, before performing integration tests, the described pre-tests in section 6 need to be passed, to make sure the operations of the Robot and Drone are sufficiently stable and accurate. All sensors need to be functional and calibrated. All network connections have to be established with a control computer, which represents the control room.

The robot and drone need to operate in a suitable weather condition, no rain, no snow, a wind speed less than 9m/s and a temperature 0° to 40°C.

The devices batteries (Robot, Drone, MIMS) need to be fully charged before the test.

In the laboratory where the tests were performed, the energy source with 220V is required, as well as a broadband network connection.

7.1.2 Test inputs

The robot had to be controlled using manual control and the semi-autonomous exploration algorithm in an outdoor- and indoor environment. The environment has to contain obstacles (like Pedestrian; Car and Dogs), which the ODS can detect, and it has to be sufficiently safe for robots and drones to operate in, in case of malfunction. Unexpected behavior and events should not lead to personal or structural damage to the environment or devices.

The drone’s video stream server configuration was setup in the application installed in the Windows laptop to be used with the drone’s remote control. The drone was flown on a predefined path and transmit the video to the DJI SDK windows application. The remote-control tablet was connected to a windows DJI SDK based application. This application collected information about the location, the camera position, the camera orientation and the battery level to transmit it to the Data Lake which sent the data to the COncORDECONCORDE platform. The live video could also be stream to a server from the DJI SDK windows application.

7.1.3 Main expected test results

It is expected that the robot correctly navigates in a Search & Rescue environment. At no point, there should be a collision with the environment or (moving) obstacles. During semi-autonomous navigation, the robot should never get stuck without ever completing the goal. In case of imminent collision, the robot should stop the autonomous operation.

For the Obstacle Detection System, the main expectation is the detection of three types of elements during the Robot movement: Pedestrian, Cars and Dogs. The output of the ODS SW will be forwarded to the Robot in order to hard stop its operations. Moreover, the Robot Driver will be supported with ODS data processing visualization: camera images enhanced with detected objects and 3D environment with LiDAR data enhanced with tracked objects.

The MIMS Box will be able to communicate the Chemical data to the Control Room through an Ethernet hub installed on the Robot Platform.

The Drone will provide an overall view of Robot operations providing another important information to the Robot Driver in order to navigate on a S&R environment.

7.2 Test procedures

This paragraph lists all the tests foreseen for each component of the Platform.
Most of the tests are linked to the Design described to the paragraphs reported in the previous paragraphs.
This procedure will be used during the Use Cases foreseen for the specific technology.

7.2.1 Robot Test Procedure

7.2.1.1 List of Visual Tests

Table 3: List of Visual Tests for Robot

Test #	Test Description
1	Verify that the robot components are mounted properly and are not loose. All rigid parts should be stable on the frame, tires should be filled with air and cables must not hang close to the wheels.
2	Verify that the dynamic parts of the robot are in the correct state. In particular, since the pan-tilt unit is not used during operation, it should be facing the forward direction of the robot. If that is not the case, it can be manually adjusted using the rotary control switches on the back of the pan-tilt unit
3	Turn the robot on by pressing the ON button on the back. Lights on the buttons indicate that the system is running. The motor light should be blinking in blue, which means they are initially disabled.
4	The robot will perform a calibration of the pan-tilt unit on startup. Fix the rotation manually if needed as described in 2, in case the unit does not directly face in the forward direction of the robot.
5	Check the network connection of the robot. It should provide a SeekurJr access point. After connecting to this access point, it should be able to reach the robot address, as well as all the components on the robot, in particular the ODS computer, otherwise ROS will not be able to establish a data connection for visualization of the data coming from that particular component.
6	Open Rviz on the remote computer and validate the visualization of the published data. This includes the camera images (resolution, frequency, colors), LiDaR point cloud and generated map. Validate the latency of the incoming data by moving something across the camera images and looking at their visualization on the remote computer.
7	Turn the motors on by pressing the MOTOR button on the back side of the robot. The light should go from blinking to constantly on. This indicates that the motors are now operable, which completes the final step of the robot initialization.

7.2.1.2 List of Functional Tests

Table 4: List of Functional Tests for Robot

Test #	Test Description
1	Test the robot motion by sending a velocity command as ROS message, either with a teleopt node (keyboard or controller) or as direct message through a console. The robot should start moving according to the velocity command.
2	Validate that the robot is capable of climbing elevations like small objects and stairs without losing stability

Launch the exploration mapping node and check if the exploration map is highlighting the right areas for exploration in the visualization. If it does, the robot should be able to navigate towards that area and explore it without any faults or collisions.

7.2.2 MIMS on the Robot Test Procedure

7.2.2.1 List of Visual Tests

Table 5: List of Visual Tests for MIMS

Test #	Test Description	Test Prerequisite	Expected Result
1	Verify that the masses of key compounds for monitoring a possibly hazardous environment are displayed on the MIMS PC-screen	The MIMS operates sufficiently; good vacuum status and sensitivity	On-line monitoring of chemical compounds of interest
2	Verify that the alarms of possible hazardous environment are displayed on the notification page of the CONCORDE	The chemical data recorded by the MIMS are transferred to the COncORDECONCORDE	Situation awareness /Display of the respective alarm messages

7.2.2.2 List of Functional Tests

Table 6: List of Functional Tests for MIMS

Test #	Test Description	Test Prerequisite	Expected Result
1	Verify that the MIMS box is correctly mounted on the Robot	Metallic brackets or straps are needed	The MIMS peli box is correctly mounted on the Robot
2	Verify that the MIMS power bank (battery peli-box) is correctly mounted on the Robot	Metallic brackets or straps are needed	The battery peli box is correctly mounted on the Robot
3	Verify that the MIMS box is correctly powered by the battery peli box	The MIMS box is stably connected via power cable with the battery peli-box ; both need to be correctly mounted on the robot	The MIMS is powered by its battery and has an autonomy of about 2.5 to 3hours
4	Verify that the MIMS's chemical data can be transferred to the CONCORDE platform	The MIMS box and its battery are correctly mounted on the robot/Wifi is available	Communication of the MIMS device with the CONCORDE platform providing with alarms
5	Verify that the MIMS peli-box is connected to the Robot through Ethernet connection	The MIMS box and its battery are correctly mounted on the robot	The MIMS device can communicate with the command center external network

7.2.3 ODS on the Robot Test Procedure

7.2.3.1 List of Visual Tests

Table 7: List of Visual Tests for ODS

Test #	Test Description	Test Prerequisite	Expected Result
1	Verify that the stereo camera frames are correctly displayed by the WebApp in the camera viewer	The ODS board is correctly receiving the required ROS messages	The Robot driver is able to correctly view the camera frames
2	Verify that the LiDAR points are correctly displayed by the WebApp in the 3D viewer	The ODS board is correctly receiving the required ROS messages	The Robot driver is able to correctly understand the 3D environment
3	Verify that the tracked points are correctly displayed by the WebApp in the 3D viewer	The ODS board is correctly receiving the required ROS messages. At least a trackable object must be present in the environment	The Robot driver is able to correctly understand the location of the tracked objects
4	Verify that the camera frames displayed by the WebApp are consistent with respect to the scene	The ODS board is correctly receiving the required ROS messages	The Robot driver is able to follow the movement of the Robot by using the WebApp camera frames
5	Verify that the point cloud displayed by the WebApp are consistent with the 3D environment	The ODS board is correctly receiving the required ROS messages	The Robot driver is able to follow the movement of the Robot by using the WebApp 3D viewer
6	Verify that objects of interest are correctly displayed by the WebApp in the camera frames	The ODS board is correctly receiving the required ROS messages	The Robot driver is supported in the localization of object of interest using the camera frames

7.2.3.2 List of Functional Tests

Table 8: List of Functional Tests for ODS

Test #	Test Description	Test Prerequisite	Expected Result
7	Verify that the ODS PELI box is correctly mounted on the Robot's brackets	None	The PELI box is correctly mounted on the Robot's bracket
8	Verify that the ODS PELI Box is correctly powered	The ODS PELI box is correctly mounted on the brackets	The green LED on the box is turned on
9	Verify the the ODS PELI box is correctly connected to the Robot through Ethernet connection	The ODS PELI box is correctly mounted on the brackets, and it is powered on	The ODS board can communicate with hosts on the same network
10	Verify that the ODS Docker Containers are up and running and that ROS messages are exchanged	The ODS board can communicate with hosts on the same network	The ODS can receive and send ROS messages

11	Verify that the ODS WebApp is correctly reachable from an external host	The ODS PELI box is powered on, the Ethernet connection is OK and the WiFi/4G configuration is OK	The ODS WebApp is accessible from a browser by requesting the configured IP and port
12	Verify that the WebApp can handle up to two connected clients simultaneously	The ODS board is correctly receiving the required ROS messages	The two clients are able to use the WebApp simultaneously
13	Verify that the ODS is able to detect and track movements of car objects at a predefined distance (e.g. 5 meters in front of the robot)	The ODS board is correctly receiving the required ROS messages. At least a car must be present in the predefined range	Vehicles present in the defined environment are correctly detected and tracked
14	Verify that the ODS is able to detect and track movements of people at a predefined distance (e.g. 5 meters in front of the robot)	The ODS board is correctly receiving the required ROS messages. At least a person must be present in the predefined range	People present in the defined environment are correctly detected and tracked
15	Verify that the ODS is able to detect and track movements of dogs at a predefined distance (e.g. 5 meters in front of the robot)	The ODS board is correctly receiving the required ROS messages. At least a dog must be present in the predefined range	Dogs present in the defined environment are correctly detected and tracked
16	Verify that the ODS tracking messages are correctly sent to the Robot driving logic	The ODS board is correctly receiving the required ROS messages.	The ODS can send tracking messages on the predefined ROS topic

7.2.4 Drone Test Procedure

For testing the drone. We mainly focus on the testing of the application with the drone and the other integration system components since the hardware is a commercial solution. Hereafter we do not distinguish between visual and functional testing.

Table 9: List of Tests for Drone

Test #	Test Description	Test Prerequisite	Expected Result
1	Verify the connection between the remote control and the drone application (on the Windows laptop) and the connection between the remote control and the drone.	The drone application should be installed. The state of the connection should be "connected" on the application user interface.	The drone operator can see near real time drone data such as position of the camera from the user interface and communicate with the drone.
2	Verify the connection with the MQTT server.	The drone application should be installed. The machine where the drone application is installed should have internet connection. From the application, the data stream could be started and stopped. An MQTT client like MQTT X could be used to track the data received from the broker side.	The MQTT client should display the near real time Json data received from the broker.
	Verify the writing in the logger.	The drone application should be installed. The file where Json data will be stored should be selected.	After the stop of the text data streaming. The recorded data should be retrieved in the selected file.
3	Verify that the view of the camera is visible to the operator.	The drone application should be installed. The application allows to display the view of the camera of the drone.	The drone operator can see the view of the camera of the drone.
4	Verify the connectivity with the streaming server.	The drone application should be installed. The machine where the drone application of the drone is installed should have internet connection. Streaming should be started and a client like VLC player could be used to see the streamed video.	The view of the camera of the drone should be visible in VLC player.
5	Verify the recorded video data.	The drone application should be installed. The machine where the drone application of the drone is installed should have internet connection. After	The drone operator should retrieve the recorded video as file.

		a predefined streaming duration, the recorded video should be retrieved.	

8 Test results

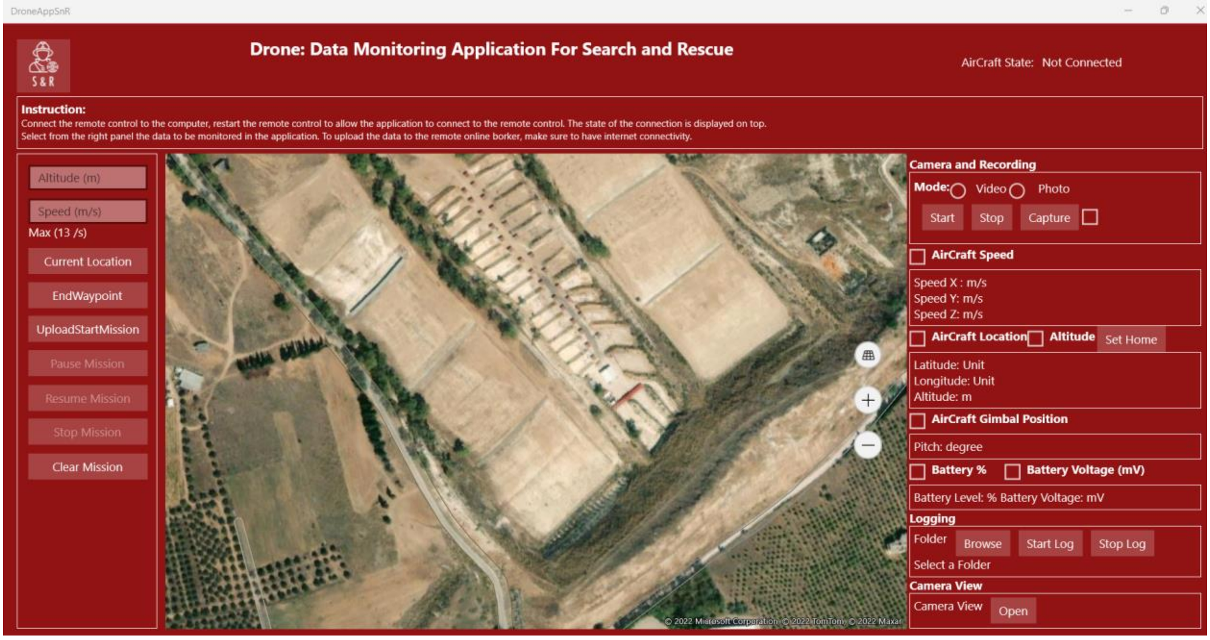
8.1 Summary of test results

8.1.1 Drone Application test results

During the UC4, the functioning of the drone application has been tested as follows:

- Transfer of the video recorded files to the HDFS remote directory
- Stream of the text data to MQTT broker and to Kafka topics.
- Monitoring of real-time data of the drone data.
- Logs of the flight data in a local file.
- Start and stop the video recording and the capture picture onboard the drone.
- Display of the camera view of the drone.

All the features provided by the application are functional. The data communication from the drone to the remote control (wireless: OcuSync 2.0) and from the remote control to the application (wired connection) provided a near real-time data transfer. However, the communication to the remote file storage system and to the streaming server was slow because of the type of data to transfer (videos) and the speed on the connection. The stream of the light text data to Kafka topics did not encounter any issue.



DroneAppSnR

Drone: Data Monitoring Application For Search and Rescue

AirCraft State: Not Connected

Instruction:
Connect the remote control to the computer, restart the remote control to allow the application to connect to the remote control. The state of the connection is displayed on top.
Select from the right panel the data to be monitored in the application. To upload the data to the remote online borker, make sure to have internet connectivity.

Speed X : m/s
Speed Y: m/s
Speed Z: m/s

Latitude: Unit
Longitude: Unit
Altitude: m

Pitch: degree

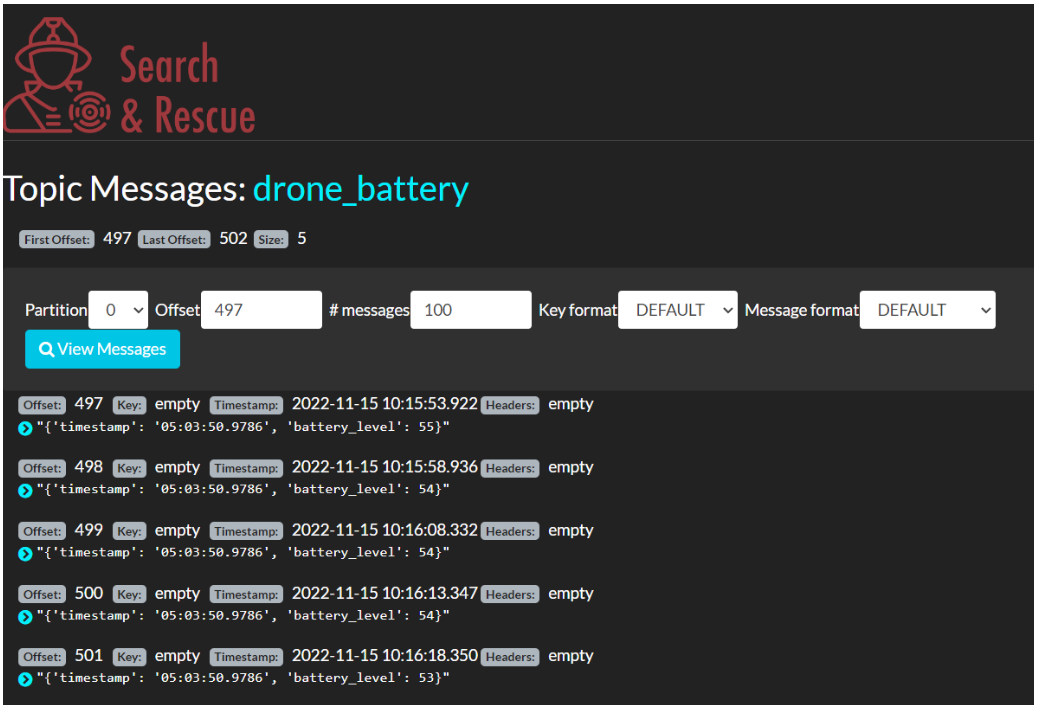
Battery Level: % Battery Voltage: mV

Folder
Select a Folder

Figure 31: Screenshot of the drone application

The application allows also to create an automatic execution of a waypoint mission. This feature was not used during the UC4 because the zone is a military zone that is protected by a DJI geo-zone in which the execution of a waypoint mission is not allowed by the drone's manufacturer DJI. Since the DJI SDK is used in the Windows application, this feature was locked and not testable during UC4. The video of the drone was also streamed to a streaming server, due to limited speed of the internet connection, the streaming service does not provide the best quality and the file transfer was slow.

Figure 32: Creating waypoint mission from the Drone application interface



Topic Messages: drone_battery

First Offset: 497 Last Offset: 502 Size: 5

Partition 0 Offset 497 # messages 100 Key format DEFAULT Message format DEFAULT

```
Offset: 497 Key: empty Timestamp: 2022-11-15 10:15:53.922 Headers: empty
"{'timestamp': '05:03:50.9786', 'battery_level': 55}"

Offset: 498 Key: empty Timestamp: 2022-11-15 10:15:58.936 Headers: empty
"{'timestamp': '05:03:50.9786', 'battery_level': 54}"

Offset: 499 Key: empty Timestamp: 2022-11-15 10:16:08.332 Headers: empty
"{'timestamp': '05:03:50.9786', 'battery_level': 54}"

Offset: 500 Key: empty Timestamp: 2022-11-15 10:16:13.347 Headers: empty
"{'timestamp': '05:03:50.9786', 'battery_level': 54}"

Offset: 501 Key: empty Timestamp: 2022-11-15 10:16:18.350 Headers: empty
"{'timestamp': '05:03:50.9786', 'battery_level': 53}"
```

Figure 33: Json data transferred from the drone application

From the test use case, we can see that the network connection quality plays a major role in the quality of the data provided specially for wideband data. Also, wireless connectivity (from the remote control to the laptop) provides a better flexibility for the pilot of the drone. This would give the pilot the ability to move while operating the drone via the remote control and the windows application.

8.1.2 RESCUE-MIMS on board DFKI's robotic platform results

In UC3 it was confirmed that the robot is able to navigate on open terrain and inside buildings without losing connection. It was tested, if the robot can be operated b firefighters in closed buildings, as shown in Figure 34. This served as a preliminary test for mounting the RESCUE MIMS, as the robot is expected to behave similarly with a payload. For a physics test, the robot was simulated with the RESCUE MIMS payload to estimate the maximum step height the robot can climb without falling over, which resulted in an approximate elevation of 22cm, see Figure 35.

Figure **34**: SeekurJr Robot in operation in Tulln fire accademy

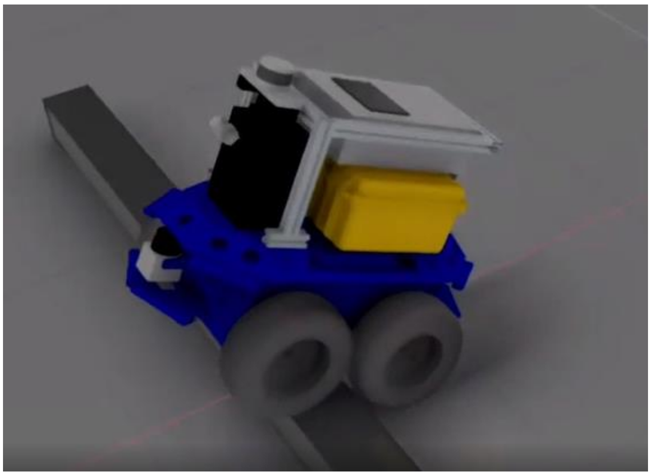


Figure **35**: SeekurJr physics simulation for maximal climb height

Prior the UC4, testing took place by NTUA and DFKI people on the integration of the respective technologies, the RESCUE-MIMS and the SeekurJr robot in respect. For implementing these experiments, the Hellenic Fire Academy premises in Athens have been provided with the contribution of EPAYPS who was the UC4 leader. The testing included the following:

- Hardware Integration testing

In order to mound the RESCUE-MIMS and its battery pack on the robot, DFKI people had created a metallic frame with certain dimensions (See Figure 28). Specific type of straps and Velcro tapes were used to keep the different components stable together (for more details see D5.7). The nozzle of the RESCUE MIMS was attached to the Pan-Tilt Head of the robot. However, due to too much strain it was not safe to actually turn or tilt the Head with the nozzle, so it remained in a fixed horizontal position.

Figure 28: Final configuration of the SeekurJr DFKI robot after hardware integration of the RESCUE-MIMS device and its battery by NTUA

- Stability testing

After the hardware integration, the final configuration shown in Figure 29 was tested in the open field of the Hellenic Fire Academy for its stability, in order to be ready for the field site at Corinthos area (See Figure 30). The preliminary tests were successful. The robot was able to connect to the created network and send obstacle and control data. The localization and mapping of the area worked flawlessly. The autonomous exploration was tested on a free area and the robot moved fully autonomously around the area to map the environment given a local goal inside a garage without colliding with any objects.

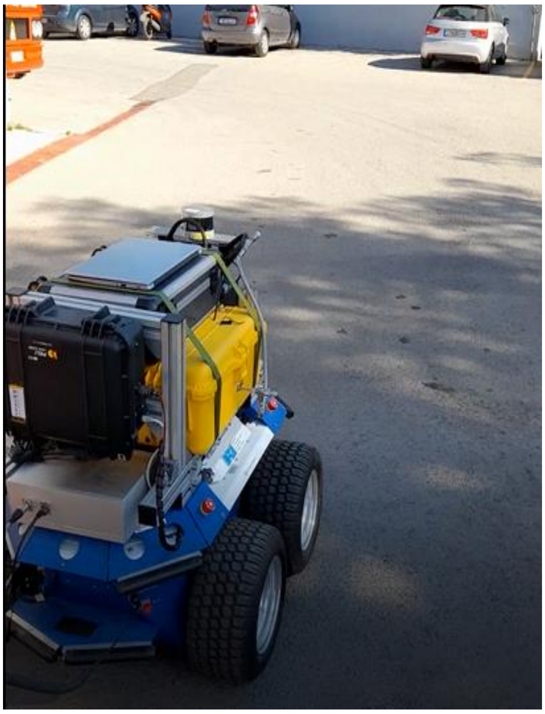


Figure 29: Stability testing of the final configuration of the SeekurJr robot at the open field of the Hellenic Fire Academy, Athens

Before the final demo however, the system lost power to the 12V regulator, which resulted in the loss of most devices on the frontal sensor tower, in particular both LiDaR sensor shut down. Attempts to restore the power supply through other 12V lanes resulted in other shortcuts and shut off. Without LiDaR data proper localization and mapping was only possible through the cameras. Autonomous exploration was impossible due to the lack of those sensor. The ODS was also only able to operate on Camera data only due to missing LiDaR data.

Figure 30: The RESCUE-MIMS (NTUA) on-board SeekurJr robot (DFKI) operating in UC4 simulated industrial fire scenario at Corinth field area, Greece

8.1.3 On-board ODS system

The on-board ODS system was tested in UC3 and UC4.

8.1.3.1 On-board ODS system in UC3

The ODS was tested as an on-board object detector and tracking system during UC3 at Tulln, Austria, in October 2022, with the purpose of testing its capability of providing information about nearby obstacles that could collide with the DFKI robot. The output of ODS was used to feed the robot steering algorithm in order to prevent it from moving further in case an object (person, dog, car) was detected to be too close, resulting in a possible collision.

Figure 36: Web viewer screenshot of person detection. In the lower part the visual show of contributions from several sensors.

All visual and functional tests described in section 7.2.3 were performed and passed by the ODS during UC3. Particularly, the ODS succeeded in notifying the steering system, during the robot operations, of the presence of obstacles in front of him, forcing it to stop to avoid a collision. Information about the sensing of the environment and the detected objects were provided to the user by means of a dedicated viewer, served by ODS as a web page that can be used in a web browser.

During the tests, a problem in the accurate positioning of the targets detected by the stereo camera was noted, as their distance from the robot appeared to be overestimated, particularly at a distance. This inaccuracy was almost irrelevant and had no effect at close distance. Nevertheless, Thalit/GTS addressed the problem after UC3 with the aim of testing an improvement in UC4.

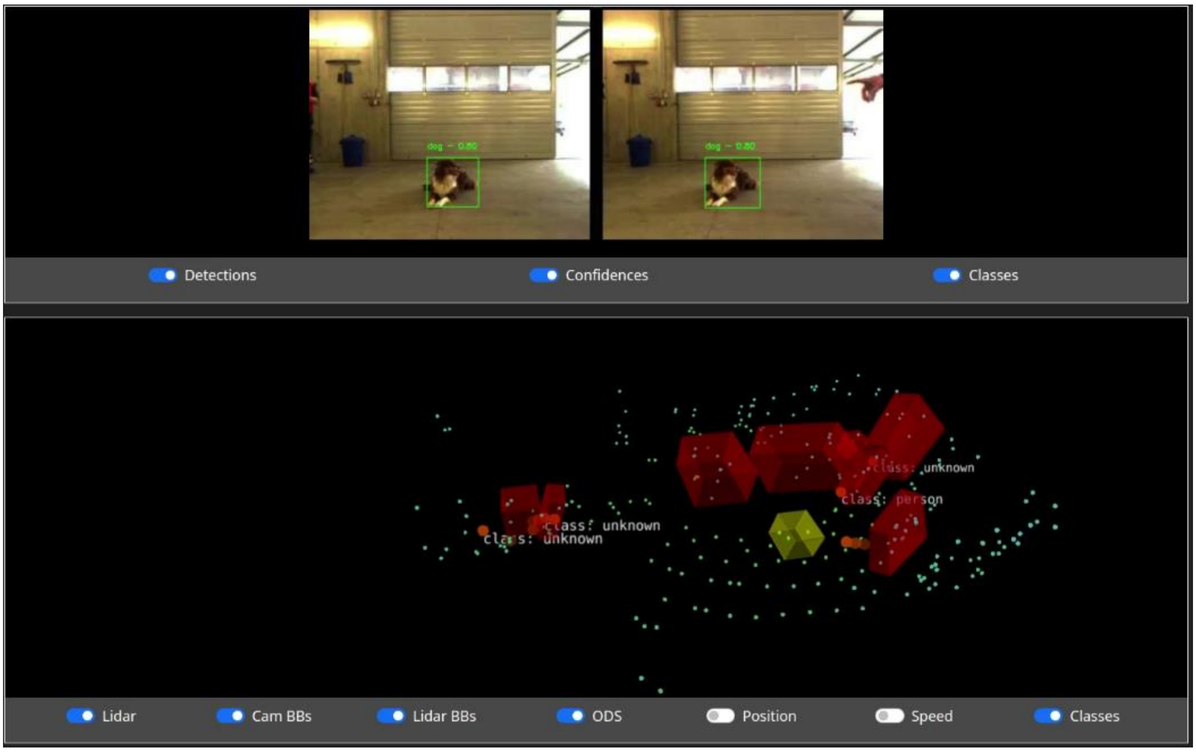


Figure 37: Web viewer screenshot of dog detection. In the lower part the visual show of contributions from several sensors.

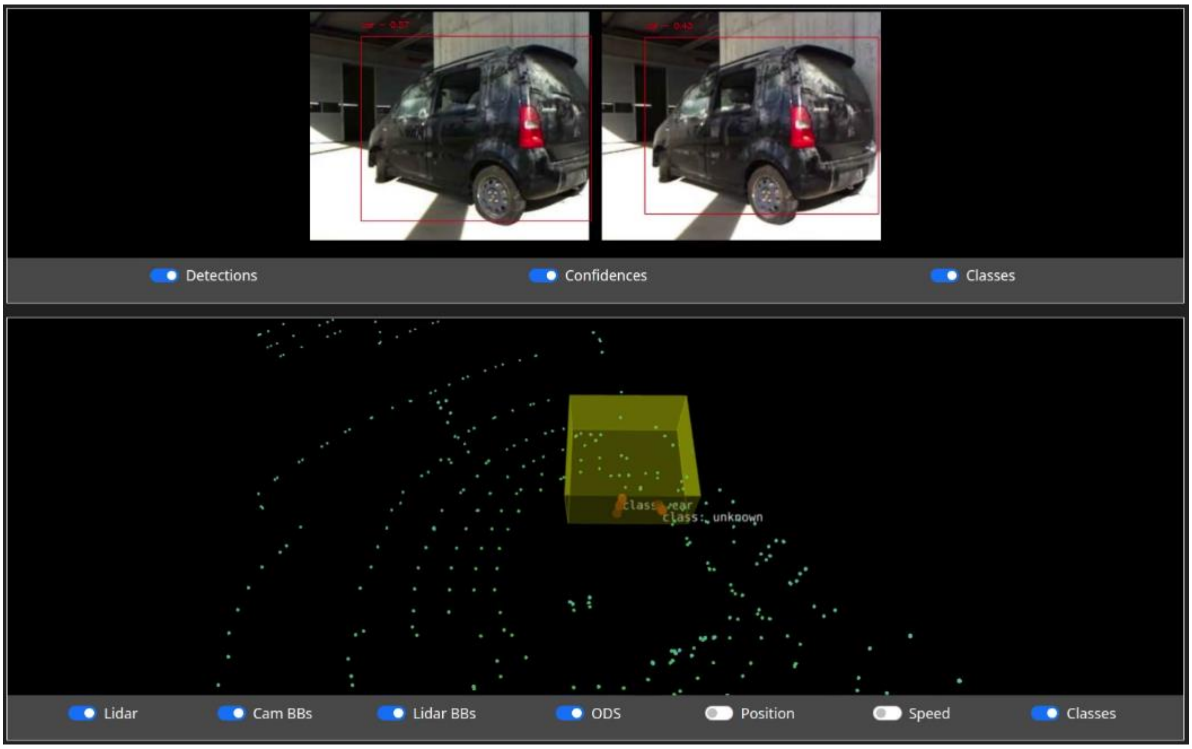


Figure 38: Web viewer screenshot of car detection. In the lower part the visual show of contributions from several sensors.

8.1.3.2 On-board ODS system in UC4

During the preparatory phase of UC4 in Korinthos, Greece, in November 2022, the DFKI robot underwent a major failure. Some of the on-board devices were broken by what is believed to be a short circuit that occurred for unknown reasons. Consequently, the DFKI robot had no operational lidar sensor and the ODS system had to run using input from the stereo camera only. This limited the effective field of view of the ODS to a narrow cone in front of the robot, since a wide-angle sight is only possible with an operating lidar sensor.

Figure 39: Web viewer screenshot of person detection after the latest upgrade Yellow circles clearly mark persons. In the lower part, the visual show does not include LiDAR contribution.

After UC3, Thalit/GTS made a few improvements on the ODS. In particular, a novel method to locate targets in 3D with the stereo camera was adopted, to achieve both a higher rate of detected objects and a better accuracy in locating them. Its results were supposed to be compared with the results of the object detection on the lidar data, but that was not possible due to the failure of the lidar sensor. However, even if a comparison of the results of the two object detectors was not possible, the stereo camera was enough accurate to allow an operator to drive the robot at a distance showing the position (and the class) of the detected obstacles (persons, dogs, cars) on an updated and improved version of the dedicated 3D web viewer.

Due to the above circumstances, not all the tests in section 7.2.3 could be performed during UC4. However, they were already tested (and passed) in UC3. Those that were repeated during UC4 passed as well.

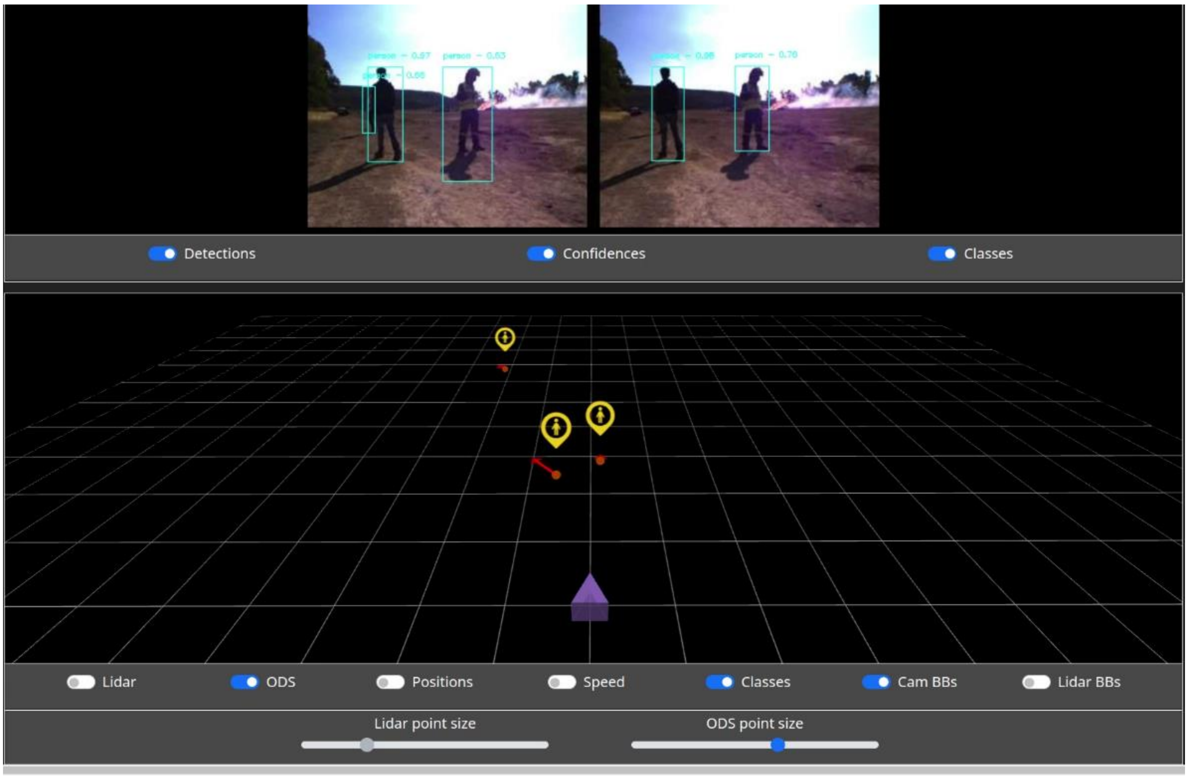


Figure 40: Web viewer screenshot of person detection after the latest upgrade Yellow circles clearly mark persons. Note that system detects a third person whom is almost invisible in the image.

8.2 Problems encountered

The robot-RESCUE MIMS system used in UC4 evaluated was found to be suitable for search and rescue operations in industrial areas and of great help for decision support with the combination of vision, sound and the knowledge of concentrations, before setting the fire fighters and go in action to rescue or extinguish the fire (for more detail see D5.7). The only issue that was successfully solved was that of recharging the batteries of the robot the previous day of the trial.

8.2.1 Problems encountered for ODS

During UC4 a possible detection problem has been noted. Persons laying on the ground are very likely NOT to be detected by the ODS, for two different reasons:

1. The CNN used to detect objects of interest on the camera images is not trained for persons in that specific pose
2. Given the camera positions (at about 70 cm of height, looking ahead with optical axes parallel to the ground) and the amplitude of the vertical field of view, a person laying on the ground disappears from the images when it is still a few meters away from the “safety region” of the robot (i.e. the region where any object found would prevent the robot from moving further).

The problem can be addressed in a twofold manner:

1. Re-train the CNN adding to the dataset images of persons laying on the ground.
2. Adopt wide-angle lens or change camera orientation or position. Please note that these countermeasures may have an impact on the robot main systems and thus should be discussed together with the DFKI team. Another possibility would be to use a different pair of cameras.

A different problem that occurred both in UC3 and UC4 regards wireless connectivity. Despite all efforts from the partner to provide reliable and wide-spread connectivity, problems arose in both use cases, that prevented the robot from being accessible from the control center. This prevented the ODS interface from being accessible at a distance greater than a few tens of meters (the range of a portable backup Wi-Fi access point).

8.3 Recommended improvements

Based on UC4 results, regarding the final configuration of the RESCUE-MIMS on board the SeekurJr robot, it seems that it could work fine in case of an industrial accident, but it does not seem ideal for a forest fire because of the roughness of the terrain that may cause inversion of the robot; other type of wheels capable of climbing are suggested. Moreover, for both the RESCUE-MIMS's components, as well as the robot, the issue of thermal resistance should be taken into consideration, especially when they are supposed to be used in fire incidents (for more details see D5.7).)

8.3.1 Recommended improvements for ODS

In order to address the problem reported in section 8.2, it is recommended to do the following:

1. To improve the effectiveness of the CNN in detecting of persons laying on the ground, the CNN should be retrained on a dataset augmented with examples (images) of people laying on the ground.
2. To improve detectability of persons laying on the ground, it is recommended to enlarge the vertical field of view of the stereo camera pair, so that the person will remain visible even at close distance
3. To improve remote long-range connectivity, we recommend to use 5G communication technology over Wi-Fi.

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