European Commission

System for virtual TELEportation of RESCUER for inspecting coal mine areas affected by catastrophic events

(TeleRescuer)

FINAL REPORT

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System for virtual TELEportation of RESCUER for inspecting coal mine areas affected by catastrophic events

(TeleRescuer)

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1. FINAL SUMMARY

The goal of the project was to develop a system for the virtual teleportation (virtual immersion) of rescuers to the subterranean areas of a coal mine that have been closed due to a catastrophic event within them. Nowadays, human rescuers inspect such areas. The activity of rescuers is extremely dangerous. Moreover, human rescuers are only allowed to enter a restricted area if the values of several critical parameters achieve acceptable levels, which often requires long waiting times.

To overcome these problems and improve the efficiency of operation of human rescuers, a TeleRescuer system was developed. The TeleRescuer system takes advantage of a special unmanned vehicle (UV) capable of moving within the area affected by the catastrophic event (i.e., with many obstacles, such as parts of damaged machinery and equipment, fallen rocks, damaged installations, etc.). The UV is equipped with sensors and video cameras. A breakthrough in the operation of such UVs depends on the real possibility of virtual immersion (virtual teleportation) of the rescuer to the area of operation, which is achieved by combining three key technologies. First, particular attention was paid to the interface of the rescuer/UV, the goal of which was to make possible direct action in the inspected area while the operator remains in a safe place. To this end, both virtual and augmented reality were widely applied. Second, to allow this virtual teleportation, a very powerful communication system was developed to allow for the broadband broadcasting of videos, results of measurements, and the virtual, direct control of the UV and its sensors and effectors. Third, a very realistic simulator and operator's station were developed to allow for the testing of the interface and to train rescuers in controlling and using the UV during the rescue operations in a representative environment. Individual systems were integrated together and then tested in laboratory conditions as well as real conditions in a harsh environment.

To achieve objectives and results envisaged the planned sequence of tasks was carried out. Initial and key tasks were associated with the work package **WP1 Detailed identification of needs, formulating requirements.** The identification of the needs connected with the following issues has been carried out in close collaboration with the Central Mining Rescue Station (CMRS): mobility of UV, measurement of physical quantities, image/video transmission, communication and control, navigation in known/unknown environments. Within the task **T1.1. Identification of the needs** the rescuers filled out special questionnaires. Additionally, interviews with experienced rescuers and discussions with the higher engineering personnel of CMRS were performed. Results of those activities were summarized and reported (in a report presenting needs and requirements).

Issues concerning mobility were analysed within the task **T1.2. Analysis of the issues concerning the mobility of UV**. CMRS and other Beneficiaries have identified types of obstacles that the UV could be faced with during the inspection of roadways and other areas affected by a catastrophe. The obstacles can include parts of machinery, equipment, materials used by miners during their work. Furthermore, there are possible different conditions of soil, and finally large pieces of coal or stone. CMRS identified also safety requirements which must meet the requirements of the ATEX directive in the scope of drive - IM2, in the scope of measuring devices - IM1. There also should be located prominently the "Emergency stop" button, allowing cutting off the power and immobilizing in foreseeable emergency situations. The complete UV should fulfil at least IP 54, although IP 68 would be preferred.

Issues concerning measurements of physical quantities were analysed within the task **T1.3. Analysis of the issues concerning images and physical quantities to be measured by the UV**. The respondents suggested that the form of key information presentation on the inspection should be as simple as possible. Data from measuring devices should be presented in the numerical or percentage form or ppm depending on the component or parameter. Information should be shown on 1 or 2 screens - more of them could cause problematic operation while the operation station would be located in the underground base. It was required to carry out measurements, transmission, visualization and recording of temperature and humidity and temperature of selected elements of the robot's body in a continuous way and not absorbing the operator. Exceeding the temperature threshold had to be indicated. Operating temperature range was identified as: -5 °C - + 60 °C, the range of measurement capabilities (robot immobilized): -30 °C - + 80 °C, temperature resistance of the equipment up to + 90 °C, relative humidity up to 100% (95%). The measurement of the percentage of gases: O_2, CH_4, CO, CO_2 – once upon request by the operator or according to the schedule chosen from previously provided measurement cycles. The operator should be able to easily and quickly program the contents of the measurement cycle by the software. Indication of exceeding by a measured value the preset alarm conditions was also specified. A placement of some sensors (e.g. CH_4, O_2) was required on a vertically retractable telescopic mast (independent of the sensory arm) – allowing rising the sensors up to 3 m. Required measurements of environmental parameters and composition of the mine atmosphere were also defined (CH_4, CO, CO_2, O_2, air flow, temperature and humidity).

Issues concerning communication were analysed within the task **T1.4. Analysis of the issues concerning the communication and control.** A communication system should allow for transmission of the video stream, measurement data and UV control at effective range of minimum 1 km. An additional wireless backup communication system deployed by the UV during its movement forward to the affected area would be of great importance. Based on questionnaires, teleoperation requires live transfer of audio-visual data extended by graphical indication of vital parameters of the robot and its environment. Also, there is a need of 3D vision (stereovision) to allow better control basing on information concerning distances and relative placement of different obstacles in the scene of operation of the robot (in remote control mode), and to increase the effect of virtual teleportation of the operator to the working scene of the robot. Requirements with respect to a housing of the UV's controller (its shape and functions) have not been clearly defined by the rescuers. A gamepad-like controller was acceptable, but there were different opinions on that matter.

Issues concerning UV control by an operator were analysed within the same task **T1.4.** Images should be taken by at least 5 colour cameras. Field observation by cameras – in front of and behind the robot, two in each direction, wherein at least one of them should be movable in the horizontal axis (± 45 °). Equipping this camera with varifocal lenses would be of great advantage. This would allow simultaneous observation of the field from 2 independent cameras from different perspectives, eg.: general view and zoom or general view with far perspective. Respective lighting of the field of view for each camera with adjustable light intensity to eliminate glare and scattering on water mist (warm colour) was required. Optional flash for the selected camera could be helpful. The UV should contain an arm with the cameras and an independent arm with the measuring probe, which would be able to operate within a number of degrees of freedom.

Issues concerning navigation and autonomous operation were analysed within a task **T1.5. Analysis of the issues concerning navigation and map building**. It was decided that three states of the UV operation and navigation will be implemented. Normally the robot has to be operated remotely through a fibre optic cable. In case of breaking the fibre optic cable the UV has to be wireless controllable. Deployed motes should allow retaining communication. In these two states an autonomous operation was not considered. Once of the robot had to operate by the wireless (radio) network only, without fiber optic cable transmission, it should be able to navigate autonomously. The UV at least should try to trace back its movement path and go back to a place where it would be possible to re-establish the radio connection. If return attempts were unsuccessful, the UV should be able to hibernate, reduce activities to taking measurements and data logging and wait for the rescue. In case of autonomous operation, it has been identified that a navigation had to be realised on the base of odometry and/or 3D maps. These maps should be built during normal operation of the UV.

A summary of all the analyses was realized within a task **T1.6. Formal specification of requirements.** A formal report containing detailed requirements was prepared. These identified requirements and needs constituted the base for future work in the framework of work packages **WP2 Research into the UV** and **WP3 Research into virtual teleportation technology and development of a training simulator.**

The final result of the task **T2.1. Research into the mechatronic subsystem of the UV** is a mobile platform supported on four movable arms equipped with caterpillars. The UV is equipped with accessories for communication and advanced inspection of an affected area of a coal mine. The main mechatronic component is the platform itself, as it serves as a base for mounting and carrying every other part of the system (excluding the operator station). Two main features of the platform are high mobility and high level of protection. High mobility means the ability to overcome most of the obstacles, but it does not require high speed of movement. As the platform has four caterpillars mounted on independent arms, it can literally climb stairs. The level of protection is meant twofold. First, the platform itself is protected from environmental factors as dust, water and temperature. On the other hand, the environment itself is also protected from the threats that the platform introduces while operating in an explosive atmosphere. For this reason, all but one subsystems have been designed and manufactured to comply ATEX M1 standards. However, the work to reconcile the two objectives simultaneously – the mobility and protection - was extremely hard. The most important mechatronic accessories and subsystems mounted on the platform are: the arm with the camera cylinder and sensor mast, laser scanner, mote releaser and optic fibre unwinder. Every component has to comply to the same protection level as the platform. The arm with the cylinder is the platform main accessory. It is responsible for positioning the cylinder where sensors and cameras are mounted. Because of environmental restrictions, it is one of the most complicated modules. There are also mechatronic parts of the communication system – the fibre reel unwinder and the mote releaser. The last accessory is rotating laser scanner used for 3D mapping.

The final results of the task **T2.2. Research into the communication system and sensory system** are the communication system as well as sensory system and vision system dedicated for the UV which operates in harsh underground conditions in coal mines. Two possible solutions for providing a broadband communication system are implemented: a wireless communication system and a wired system using optical fibre cable. The developed communication system can typically be used within the range of 500 m, depending of the configuration of roadways under inspection. The developed mote dispenser is capable of releasing wireless motes while the robot moves on. Prototypes of these two systems were implemented and tested in different environmental conditions. A wireless communication system acts as a backup system in case when the optical fiber is broken. The optical fiber drum contains 2 km of the optical fiber, and it is mounted on the robot. Thus, a long distance of 1km (+1km to come back) is reached. For the wireless system 8 wireless motes are developed. A distance of 80m between motes is reached according to real measurements made in a real coal mine. Thus, up to 560m can be reached, which satisfies the requirements. A mote dispenser is developed and installed at the robot containing all the motes. A point-to-point communication with the operator is established what allows releasing a new mote when the respective command from the operator is received. Measurements of signal strength are made regarding the wireless link performance to assure continuous communication with the operator site.

The developed sensory system is capable of measuring quantities of CH4, CO, CO2, O2, temperature, humidity and air flow. The developed vision system together with LED lighting is able to take videos inside the coal mine. A vision system is developed and formed by one stereoscopy camera, 2 wide-angle cameras and one thermal (IR) camera. All the systems are ATEX-compliant and are able to work in a real environment. All the initial requirements are satisfied. Prototypes of each system were developed. The applications of these systems are numerous: to drive any unmanned vehicle remotely and guarantee immersive experience to the operator, monitoring gases in any place, any communication where broadband one is needed, any wireless communication system where the topology is changing, etc.

The final result of the task **T2.3. Research into the control system** is a Main Control System (MCS) which allows for the movement and function of various parts of the UV. The developed MCS is based upon an industrial PC board with ultra-low-power CPU (TPD 4.5W), 4GB memory and 512GB SSD HDD, with Ubuntu Linux operating system. This main board is connected to the especially designed daughter board, which provides easy connection to other subsystems of the mobile robot. To assure safe opertion of the UV an analog signal from a methane sensor is connected to the MCS. This provides information about methane concentration level. The main purpose of the interface board is to provide communication capabilities for the PC board used. This function is realized by four RS232 lines connecting the PC board and the interface board. An important part of the Main Control System is to secure extra safety for motion control system. This is done by independent safe control of motors controllers (RoboteQ).

One of aims of the UV is the possibility to detect obstacles in the working environment and measuring distances from these obstacles. Therefore, methodologies for map building and a prototype system for map building based on a laser scanner have been developed in the framework of the task **T2.4 Development of methodologies for building maps.** The developed Laser Scanner is able to detect obstacles not only in a plane, but also in 3D environment. This ability enables the operator to fully control the robot in any complicated environment even under a bad lighting condition or in a dark environment. The 3D Laser Scanner is mounted in the front of the UV on its top to have the best conditions to measure distances from obstacles around. The communication with the Main Control System (MCS) is realized by the pair of plastic optic fibre. The power supply is provided from its own batteries. Average number of points in a single point cloud is about 200 thousand. To merge the points clouds the Point Cloud Library (PCL) is used. This library implements a few algorithms for point clouds registration. The algorithm which gives the best result is the "iterative closest point". For the mine corridor it is possible to correctly register neighbouring point clouds taking advantage of additional data from odometry and data from the position sensor of the laser scanner. An application of this system is not only limited to build maps of coal mines for autonomous operation. Such a system can be applied as a separate system on any mobile platform or without it, for scanning any buildings, open areas (for technical objects), etc.

The map building issues are also connected with results obtained as part of task **T2.5. Research on methods of autonomous operation of UV in a known environment**. A system of autonomous operation consists of the following main subsystems: localization, autonomous movement control and map building, path recording, autonomous return subsystems. The localization subsystem is responsible for calculating UV current position and orientation. It is used by two other subsystems: the scanner subsystem and autonomous movement subsystem. The scanner subsystem (which takes and matches scanner point clouds) uses localization information as an initial one when performing clouds matching. The autonomous movement subsystem requires the position and orientation data for correct path finding. Localization information is also shown to the operator by the operator interface. The main purpose of the autonomous movement control subsystem is to allow for certain autonomous metabehaviors: returning to the starting point and moving to the goal given. Internally autonomous behaviors are based on the set of simple behaviors, which then combined together allow the vehicle to perform certain actions (moving and rotating). Each behavior on every algorithm iteration gives us a vector, that represents the direction and magnitude (speed) where the robot should move. The map of the coal mine galleries, which is used during autonomous return, is represented as a graph. The created map contains information about subsequent unique places, value of identification ratio, the robot position and distances between particular places. When the communication is lost (or on operator's demand), the robot is able to return autonomously according to the recorded path to the starting point or at least to the place where the communication will be restored. Systems similar to the elaborated one in the framework of this project can be applied in any applications where autonomous operation of any UV is necessary. Therefore, results are particularly implementable in many different areas.

All the elaborated subsystems dedicated for TeleRescuer UV were integrated into one system, so that the system is able to deliver the overarching functionality. It was realised in the framework of task **T2.6. System integration**. Software of the TeleRescuer control system is relatively complex because the robot contains many subsystems. Software located in the robot body (running on the MCS under Linux Ubuntu) is based on ROS – the Robotic Operation System. Data and information exchanged between individual subsystems of the TeleRescuer system are logically assigned to separate commands. Eight EC motors (4 for caterpillars motion of each tracked arm and 4 for rotation of these arms) provide movement of the mobile robot. These motors are driven by four dual-channels motor drivers connected to the MCU by CAN bus. Each driver has an independent battery pack with common ground. All subsystems are interconnected by an optical fibre or intrinsically safe metallic connections. CAN bus communication lines with metallic wires are used to control the motion subsystem motor controllers. Another CAN bus is realised by the optical fibre and is designed to provide communication with one motor controller located in the sensory arm. Communication with the 3D laser scanner is arranged by a bidirectional optical fibre link connected to an RS232 interface.

Results of the task T2.6 allowed to finalise the work package associated with the prototype of the UV. The integration of the UV was strictly connected with tasks realised in the framework of the work package **WP3 Research into virtual teleportation technology and development of a training simulator**, especially with the human-machine interface, training simulator, and the operator's station.

The goal of the initial task **T3.1. Development of the concept of a methodology and system for virtual teleportation,** related with WP3, was to review existing methods and develop an effective one for virtual teleportation of rescuers (operators). Within this task a review of methods that could be utilized in order to obtain virtual teleportation of the operator was done. Various types of stimulus that can be applied at the level of human senses were considered. We analysed methods for visual, auditory and tactile stimulations. Visual data acquisition methods were analysed, and investigation of various camera types and configurations that can allow for 3D immersion was done (e.g. stereoscopic cameras, stereoscopic vision from a single camera etc.). The same was done for visualisation methods (methods based on 3D caves, head-mounted displays, 2D/3D screens etc.). The purpose was to find as wide range of applicable solution as possible in order to be able to select the best approach for the TeleRescuer robot operator's virtual teleportation during the following parts of the project realization. Within this task the consortium analysed various possible configurations of controlling devices such as application of specialized equipment for RC planes, gamepads, joysticks etc. Results of T3.1 were utilized in the consecutive tasks during prototyping the hardware and software for the TeleRescuer robot operations.

A review of knowledge acquisition methods that can be utilized in the task of prototyping the TeleRescuer operator station and virtual teleportation was done during the task **T3.2. Research into knowledge representation.** Basing on the research two methods of knowledge acquisition were selected:

- extraction of knowledge from a domain expert by a knowledge engineer,

- extraction of knowledge from a domain expert without presence of knowledge engineers.

The decision was made to use the first approach for knowledge acquisition from the main domain expert and the latter approach for mass knowledge acquisition from the rest of rescuers. As the main domain expert MSc Eng. Piotr Golicz from Central Mining Rescue Station was selected. He has many years of experience, in the area of mining equipment utilized during rescue action conduction.
Researchers from the interested members of the consortium spoke with the domain expert about the needs of rescuers, during conduction of rescue actions, in the areas of:

- robot controllers,
- visualisation of the robot environment,
- sensor data visualisation,
- sound acquisition and tactile stimulation.

Knowledge acquisition sessions based on evidence acquired during realization of T1.1 and T3.1.
As a results of data acquisition session with the main domain expert a concept of the virtual-based teleportation system was obtained. Then in order to confirm or reject the undertaken approach two surveys were prepared. Contents of these surveys was consulted with the main domain expert. The surveys were provided to the rescuers employed in CMRS. Their task was to fill these surveys according to their experience and knowledge. Obtained results were important base during realization of the rest of tasks within WP3.

Knowledge obtained in T3.2, combined with the review conducted in T3.1, was utilized during realization of task **T3.3. Development of a knowledge-based methodology of virtual immersion**. Basing on knowledge acquisition session with our main domain expert MSc. Eng. Piotr Golicz we decided that sound acquisition as well as tactical stimulation will not be employed in the system. An auditory stimulation was ruled out because the main domain expert pointed out that the mining environment is noisy, in addition microphones installed in the robot body would mostly register noise produced by motors and mechanisms, what would be disturbing for the operator. In addition, it would make the construction of the robot body much more complex because of ATEX requirements. A tactile stimulation (such as in case of 6 DOF movement platform) was ruled out because it would require significant complication of construction of the operator station and rule abilities of easy transportation. It is important to deploy operator station close to the location of rescuers during their action because it simplifies communication between the robot operator and the rescuers involved in the action. Therefore, the operator station should be mobile one. The decision was made to base the virtual teleportation functionality on the visual system and properly designed controllers that support precise controlling of the robot movements. In the area of visual data 3D visualisation techniques for the purpose of the robot's surrounding presentation were applied. For this purpose, the decision was made to equip the robot with stereoscopic cameras, two monocular wide-angle cameras, an infrared camera and a 3D scanner. For the purpose of visualisation 3D screens with special glasses were applied. After the review of techniques for 3D visualisation the solution was selected that utilizes:

- NVIDIA 3D vision based on active shutter glasses technology,
- anaglyph technology.

In the area of the robot operation the decision was made to use plane controllers and a gamepad. This selection was made based on the experience of STR employees and the survey made in T3.2. The plane controller was selected because of simplicity of controlling the robot movements, on the other hand the gamepad, because of ability of mapping many degrees of freedom on its controllers, which allows the operator to take full control over every component of the robot.

The developed methodologies were the base for prototyping software and hardware within the task **T3.4. Prototyping software and hardware of the human-machine interface.** The TeleRescuer Human-Machine interface consists of two parts:

- hardware that is exploited for the robot movements controlling as well as delivers the platform for visualisation of the data obtained from the robot,
- software components that are responsible for the presentation of the data on provided hardware components.

Within the software area an application was implemented that allows to visualise data obtained from cameras and robot sensors, to this end various components were prepared such as stereoscopic camera visualisation with Head up display, 2D / Infrared camera visualisation control, point of cloud viewer, 3D scanner status panel, collective battery power, gauge controls, autonomy state panel, communication debug panel, controller panel, Saitek Pro Flight status panel, system log panel etc.
In the area of hardware, the specification of the workstation was defined and proper components were purchased and assembled. The analysis conducted in the area of the operator station has led to the conclusion that the operator station should be mobile. A mobile operator station (MOS) was designed in a way that it was self-contained, it had all the elements necessary to communicate with the robot, to control the robot movements and to visualise data obtained from the robot: a monitor,

3D glasses (active and passive), a plane controller, a game pad, a keyboard, a mouse, a workstation, communication devices. A custom-made case was designed and manufactured that can house all the necessary components and at the same time is durable and lightweight. In addition, a carrying frame was developed that simplifies the process of MOS transportation as well as provides place for the operator to sit during conduction of the rescue action. The purpose was to obtain the operator station that is easy to use and requires minimum number of actions to become operational.

In task **T3.5. Virtual teleportation technology integration** a communication subsystem was implemented, all components of communication protocol for the communication between the operator station and the robot were incorporated. In addition, the components implemented in T3.4 were integrated with the software classes responsible for the communication.

On the basis of requirements identified within WP1 and previous task within WP3 a visual system for training simulator and operator stations were developed within a task **T3.6. Prototyping 2D/3D visual hardware/software system for training simulator.** Software utilized in the simulation operator station (SOS) and mobile operator station (MOS) is based on the same TeleRescuer application. As a result, software employed in SOS can be used in order to control the robot's operations. SOS software was extended with modification that allows to recognize the visual signal delivered by the simulation station. For the purpose of visualisation 32-inch curved display was applied. It is bigger and heavier than the monitor installed in MOS, however it allows to obtain even higher level of immersion and comfort during long hours of training sessions.

Within the task **T3.7. Development of methods for realistic simulations**, together with the experts from the Central Mining Rescue Station (MSc. Piotr Golicz, Eng. Adam Szadurski, Eng. Jan Kozik), four scenarios of various types of rescue actions were defined. These scenarios include: inspection of an inactive mining site, inspection of a mining site after conflagration, rescue of miners staying in a provisional shelter, rescue of the miner after a corridor collapse.

A special simulator operator station (SOS) designated mainly for simulation purposes was designed and developed within a task **T3.8. Prototyping human-to-machine interface for training simulator.** The equipment utilized in the simulator operator station uses the same elements as MOS at the controlling level (gamepad, plane controller, workstation, communication elements etc.). There is a different display included in SOS that is bigger and heavier than the display applied in MOS and it has curved surface thus better supports the immersion of the operator. Utilization of the same controlling components is justified by the fact that the operator should learn how to control the real robot based on training in virtual environment. Therefore, the same components, as well as the same mapping of the controller movements to the repertoire of the robot actions were utilized.

Training simulator base in V-REP (Virtual Robot Experimental Platform) was developed and built within the task **T3.9. Training simulator software development, system integration and extensive testing**. That training simulator allows for the training of the operator. Physical characteristics of the robot such as its weight and behaviour of the tracks were taken into account. The engine of the simulator was implemented in LUA language. The simulator allows to simulate the robot operations such as the robot movement (arms / tracks, sensory mast) acquires data from virtual cameras and transfers it to the SOS etc. Communication protocols created in T3.6 were implemented. They are in accordance with the protocols utilized for the robot operation. Therefore, SOS can be connected with the robot or the simulator interchangeably. SOS was integrated with the simulator through Ethernet network and series of tests were performed which allowed for validation of SOS as well as the simulator.

Extensive testing of the whole UV with all the integrated subsystems (as result of WP2) as well as the training simulator and operator's station (as result of WP3) was done within a workpackage **WP4 Field test of the system and its components**.

Regarding to field tests of the system and its components two different environments initially were planned. Initial verification of subsystems was realized in laboratory conditions as well as in real conditions, including: tests of the system for map building (in the Queen Luiza Coal Mine, Zabrze, Poland), tests of operation with the use of batteries (in laboratory of SUT and STR and in the Queen Luiza Coal Mine), tests of the sensory system (the Coal Mine San Nicolas in Area Sueros, Spain), tests of cameras (in laboratories of UC3M). Finally, tests were realized in a training roadway in CMRS, where there are very similar conditions to real ones. This environment had to constitute real environments for the operation of the system, including the operation of real machinery such as working mining equipment, but without the hazard of explosion or fire. Before carrying out the tests a plan of tests was set up. The plan for the tests in accordance to **T4.1. Setting up the**

detailed plan of tests took into account many aspects, for example: general verification of constructional form in terms of transport requirements, preparation for the inspection mission, introduction to the inspection area, tests in the inspection area for the accepted scenarios (e.g. verification of mobility, the ability to overcome obstacles, etc., verification of cameras units, control of the ability to identify objects, verification of the functionality of the control station.

Within the task **T4.2. Carrying out the tests**, tests were carried out in a systematic way according to the plan elaborated in the previous task. During the task it was planned to check UV's capabilities and its suitability for applications in underground mining, in the space in which an accident or disaster appeared. Parameters of the robot are generally satisfactory. However, many systems of the TeleRescuer need an improvement to achieve highest TRL (TRL9) and final industrial implementation.

Regarding to the task **T4.3. Reporting the tests** and the deliverable **D4.1 A report on tests of the system and its components** a comprehensive report was produced containing all the results acquired, and the opinions of the rescuers and miners who participated in the tests, etc. The report includes a compilation of the major observations and conclusions in order to provide a set of recommendations to improve the system. Moreover, the report includes the analysis of the performance of the UV.

Besides the scientific objectives the Consortium has achieved the objectives related to the dissemination of results within **WP5 Dissemination of results** and the general management of the project within **WP6 Management and coordination of the project**. Relating to the dissemination of results of the project the following objectives have been achieved:

- An official TeleRescuer project website;
- Two thematic brochures about the project, and the scientific and utilitarian results obtained (especially concerning the TeleRescuer system);
- More than 20 scientific papers about the implementation of the individual project tasks and the results obtained;
- Two scientific seminars and more than 40 webinars intended for all contractors;
- Multimedia presentation of results obtained;
- Participating in fairs: The International Fair of Mining, Power Industry and Metallurgy in Katowice (Poland);

Relating to the general management and coordination of the project the following objectives have been achieved:

- Carrying out a Consortium Agreement;
- Preparing a detailed project specification and delegation of project tasks;
- Monitoring and controlling the project's progress;
- Ensuring fluent communication and collaboration among the partners, and motivating the team;
- Carrying out financial and technical documentation;
- Preparing and submitting the technical and financial reports according to the deadlines set by the Commission.

2. SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE RESULTS

2.1 OBJECTIVES OF THE PROJECT

The following management objectives have been achieved within the project:

- Initiating the project – the preparation of the Consortium Agreement and the detailed project specification and delegation of project tasks;
- Monitoring and controlling the project's progress;
- Ensuring fluent communication and collaboration among the partners, and motivating the team;
- Carrying out financial and technical documentation;
- Preparing and submitting technical and financial reports according to the deadlines set by the Commission.

The following technical objectives have been achieved within the project:

- Specification of typical configurations of the subterranean areas of coal mines;
- Classification of common catastrophic events in European coal mines;
- Specification of operating conditions that the UV will confront while moving through the area affected by a catastrophic event;
- Specification of the data, images and measurement results required for taking decisions about the operations to be carried out in the area affected by a catastrophic event;
- Appraisal of the characteristics of typical dams and sealing systems used for isolating the area affected by a catastrophic event;
- Specification of the requirements for broadband communication in the subterranean areas of coal mines;
- Specification of the requirements regarding the rescuer's interface to the system;
- Specification of the requirements concerning the missions of the UV;
- Specification of the requirements caused by autonomous operation;
- Specification of the requirements concerning the system to be constructed.
- An optimal solution for the mobility of the mobile platform;
- An ATEX-Ready power supply and drive system;
- An optimised mechanical structure of the mechatronic carrier of the UV;
- A broadband communication system capable of providing data for the remote control of the UV;
- A reliable communication system for sending images and/or video streams, and features of low-varying signals;
- An effective control system running on controllers of limited computing power;
- A sensory system for collecting data and signals sufficient for the remote assessment of the area affected by a catastrophic failure;
- A sensory system and methods for building maps of an unknown environment;
- A sensory system and prototype system for autonomous navigation in a known environment;
- An integrated system capable of operating in a coal mine, ATEX-ready;
- The conception of an optimal methodology and system for virtual teleportation;
- A methodology for knowledge acquisition and representation that is efficient in controlling the robot with the use of virtual teleportation (Knowledge-based Virtual Immersion of the Rescuer - KVIR™);
- Methods and technologies used as the interface between a human rescuer and the virtual teleportation system;
- The prototype of an effective rescuer-side human-machine interface;
- Optimal methods for the realistic simulation of the operations of the rescuer;
- The conception of a test stand for verifying the developed methodology;
- The prototype of an advanced machine-to-human interface used in the simulator for the implementation of the 2D/3D visual system;
- The development of augmented reality elements for the simulator;
- The prototype of a human-to-machine interface used in the simulator to control the operation of the robot;
- The approval of the methodology and the developed system by rescuers and miners.
- The correct operation of the UV in real operating conditions and the assumed kind and size of obstacles;
- The correct operation of auxiliary equipment for arranging communication and the measuring content of air across the tunnel cross-sections;
- The achievement of the assumed parameters of broadband communication in real working conditions;

- The reliable collection of accurate values of the signals measured by the sensors installed on the UV;
- The faultless operation of the video and IR imaging system, including the fusion of images;
- The faultless operation of the UV in the remote control mode;
- The reliable operation of the UV in the autonomous operation mode;
- The confirmation of the effect of the virtual immersion of the rescuer into the hazardous area of operation.

The following promotional objectives have been achieved within the project:
- The creation of an official TeleRescuer project website;
- The preparation and publication of a thematic brochure (in both printed and electronic formats) about the project, and the scientific and utilitarian results obtained (especially concerning the TeleRescuer system);
- The preparation of scientific papers about the implementation of the individual project tasks and the results obtained;
- The organisation of a scientific seminar intended for all contractors and guests;
- The organisation of a promotional seminar intended for the potential recipients of the project results;
- Participation in a mining industry fair with the presentation of the TeleRescuer system among potential customers.

2.2 DESCRIPTION OF ACTIVITIES AND DISCUSSION

2.2.1 Detailed identification of needs, formulating requirements

Within a workpackage **WP1 Detailed identification of needs, formulating requirements** the following tasks were realised:
- Identification of the needs;
- Analysis of the issues concerning the mobility of UV;
- Analysis of the issues concerning images and physical quantities to be measured by the UV;
- Analysis of the issues concerning the communication and control;
- Analysis of the issues concerning navigation and map building;
- Formal specification of requirements.

The identification of the needs has been carried out in close collaboration with the Central Mining Rescue Station (CMRS). First, the rescuers filled out special questionnaires. Additionally, interviews with experienced rescuers and discussions with the higher engineering personnel of CMRS have been performed. Results of those activities have been summarized and reported, they are summarized in the following paragraphs.

A platform should have the ability to pass many obstacles which can appear in hard underground conditions in coal mines. Minimal safety requirements are to meet the requirements of the ATEX directive in the scope of drive - IM2, in the scope of measuring devices - IM1. There also should be located prominently the “Emergency stop” button, allowing cutting off the power and immobilizing in foreseeable emergency situations. The complete UV should have at least IP 54, but IP 68 would be better. Desirable functionality would be to meet the requirements of IM1 ATEX directive for the whole robot.

Based on CMRS part of report, one of the robot’s main operation areas is the excavation site. The main equipment in that area is: a longwall shearer, a scraper conveyer and longwall shields. The figure below shows a longwall installation with the mentioned machinery (fig. 1.1). In the centre of the picture, between the shield’s hydraulic actuators and conveyor there is a passage for operating personnel. This route is also the best one for our UV. Locomotion problems will start when some of that machinery will be destroyed in result of explosion.

Fig. 1.1. Possible environments for an UV operation

Another important area of UV's operation are tunnels. They connect the operational base with the objective site of the mission. The main obstacles here are conveyors and various maintenance equipment. Lots of these are hanged, like vent tubes, power and communication cables, pipes etc. In case of fatal accident there is a huge chance that this equipment will fall onto floor and become additional obstructions in our way.

Steep slopes (up to +/- 35°) are one of greater "natural" impediment to mobility. They can be hard to climb, when surface is slippery or loose. In coal mines steep tunnels often have built-in stairs and rails, which can be helpful during climbing.

After an explosion or fire, there is a chance that the site will become significantly deformed with the possibility of highly reduced cross-section. The site affected by an accident is usually filled with scrap-metal from a former equipment and machinery. Movement in those conditions is very hard, not only because of additional obstacles in the UV's way, but also because of unpredictability of the environment. Some areas after accident may also be flooded.

Mining machinery and technological equipment are one of the most common obstacles. There has been made a list of them in the form of a table. The data in a table includes not only the equipment name, but also its dimensions, possible location and other additional information that seems to be important.

Although dominant ground surfaces are hard rocks and concrete there is a possibility of loose sand, gravel and coal. Sometimes UV can also come across wet and slushy soil. Sometimes puddles are covered with wooden platforms or parts of conveyors belts. UV's ability to climb on slopes highly depends on the soil type. It can be near impossible to drive up on slopes steeper than 25° if there won't be any obstacles that could help in climbing.

There is the high risk of insufficient visibility caused by water mist, smoke and dust. Dense smoke caused by fire can also contain particles of diameter up to 10 μm. Some of those contaminations can handicap the efficiency and resolution of our vision systems.

The occurrence of the explosive atmosphere should also be included into environmental conditions. That topic is covered in sections about ATEX. It does not affect UV's mobility directly, but it puts serious restrictions on the whole construction that will restrain some capabilities.

Other factors without direct impact on mobility are high humidity up to 100% and high temperatures. The robot should be able to move at -5° to +60°C, take measurements from -30° to 80°C and all the equipment should withstand temperatures up to 90°C (CMRS report).

The respondents suggested that the form of key information presentation on the inspection should be as simple as possible. Data from measuring devices shall be presented in the numerical or percentage form or ppm depending on the component or parameter. Information should be shown on 1 or 2 screens - more of them can cause problematic operation in the underground base.

It is required to carry out measurements, transmission, visualization and recording of temperature and humidity and temperature of selected elements of the robot's body in a continuous way and not absorbing the operator. Exceeding the temperature threshold shall be indicated. Operating temperature range: -5 °C - + 60 °C. The range of measurement capabilities (robot immobilized) - 30 °C - + 80 °C. Temperature resistance of the equipment up to + 90 °. Relative humidity up to 100% (95%). The measurement of the percentage of gases: O2, CH_4, CO, CO_2 – once upon request by the operator or by the time program chosen from previously provided measurement cycles. The operator should be able to easily and quickly program the contents of the measurement cycle by the. Indication of exceeding the preset alarm condition. Registration of the results should include time stamps. Placement of some sensors (CH_4, O_2, Th) on vertically retractable telescopic mast (independent of the arm) – allowing rising sensors up to 3 m.

Transmission of images should be realised with the use of at least 5 cameras. Field observation by cameras – in front of and behind the robot, two in each direction. This will allow simultaneous observation of the field from independent cameras from different perspectives, eg.: a general view and zoom or general view with the far perspective

Although CMRS requirements concern the vision system with multiple cameras, in consortium opinion reliability in harsh environment was more important than simple redundancy.
Communication system should allow for transmission of video, measurement data and UV control at effective range of minimum 1 km. Based on questionnaires made by Skytech Research Sp. z o.o., teleoperation needs of CMRS employees are live transfer of audio-visual data extended by graphical indication of vital parameters of the robot and its environment. Also there is a need of 3D vision. Needs for UV's controller shape and functions itself have not been clearly defined by the rescuers. A gamepad-like controller is acceptable, but there were different opinions on that matter.

Final requirements have been specified for each subsystem of the UV, including:

- Robot platform;
- Communication system;
- Sensory system;
- Control system with autonomous operation.

A specification for the robotic platform is divided into several categories: the requirements for mobility capabilities, dimensions and weight, minimum protection level and operational capabilities. The next sections define the requirements for the mechanical part of sensor and communication equipment.

- Mobility:
    - Speed: limited to 0.5m/s;
    - Slopes: up to 25°;
    - Overcoming steps: up to 25cm ;
    - Ability to overcome standard obstacles like: the longwall system, rails, ventilation dams;
    - Fording depth: 50cm;
- Dimensions and weight:
    - Ability to fit into ø800mm dam culvert;
    - Weight: less than 600kg;
- Protection level:
    - Waterproof and dust protection level: IP 68

    IP 6x – "dust tight" - no ingress of dust; complete protection against contact

    IP x8 – "Immersion beyond 1 m" - the equipment is suitable for continuous immersion in water under conditions, which shall be specified by the manufacturer;

- ATEX M1/M2 compatible;
- Temperature resistance: up to 60°C

- Operation time and range:
  - Operating time: at least 2-3h of driving and few days in the idle mode with working sensors and communication;
  - Operation range: at least 1000m.

As mentioned in the earlier chapters about the research done on communication systems, the idea of recovering the communication equipment was abandoned early as too complicated. This section presents minimal design requirements for deploying equipment for optical fibre and radio motes.

- Deploying fibre
  - Cable length: 2000m (for 1000m range)
  - Additional requirements: possibility for mounting an encoder on the spool axle
- Deploying backup radio motes (repeaters):
  - Stack capacity: 10pcs
  - Mote dimension: ø50x120, tubular shape
  - Stacking conditions: motes should be powered while stacking
  - Motes should be deployed behind the UV
  - It should be possible to deploy a mote at any moment

The measurement equipment has to be mounted on the proper height specified by the requirements from CMRS. To take measurements from the face height or under the celling, there is a need for a retractable mast and a lifting mechanism. The requirements for the mechanical design are:

- Payload – up to 1 kg;
- Maximum height: 3m above the ground level;
- Different lifting height for different sensors (up to 3m).

IMU is essential for determining UV orientation in space. To find robot's current yaw, pitch and roll and be able to follow changes of these parameters there is a need for 6 DOF IMU. That IMU consists of a 3 DOF accelerometer and a 3 DOF gyroscope.
IMU should be rigidly fixed in chassis, and its axes should be oriented in accordance with UV's axes.

There is a need for monitoring current state of position and velocity of every UV component. So that the robot should be equipped with:

- Velocity sensors at every wheel;
- Angular position sensors at arm joints in case of the platform equipped with adjustable arms;
- Position sensor in retractable gas sensors mast;
- Position and/or velocity sensor (rotational speed) on fibre optic cable unwinding mechanism.

Protection sensors, including *t*emperature sensors should be mounted in every place with high risk of a sudden temperature increase. These places are: mechanical components that can fail unexpectedly - all bearings and electrical, high-power components: motors and motor drivers.
For additional protection in electrical components there is a need to measure current and voltage at every motor.

There are three states of the UV operation. Normally the robot is operated via fibre optic cable. In case of breaking fibre optic cable the UV should be radio controllable. Deployed motes should allow retaining communication. In these two states autonomous operation is not considered.

In case of the robot operated only by radio and loosing transmission, it should be able to operate autonomously. UV at least should try to trace back its movement path and return to a place where it will be possible to re-establish the radio connection. In the worst case scenario, the robot should return to the base on its own. If return attempts are unsuccessful UV should be able to hibernate, reduce activities to taking measurements and data logging and wait for the rescue.

2.2.2 Research into the UV

Within a workpackage **WP2 Research into the UV** the following tasks were realised:

- Research into the mechatronic subsystem of the UV;
- Research into the communication system and sensory system;
- Research into the control system;
- Development of methodologies for building maps

- Research on methods of autonomous operation of UV in a known environment
- System integration.

T2.1. Research into the mechatronic subsystem of the UV

Work on mechatronic subsystem has begun with creating general concepts of a platform. Design ideas were based on the research on previously existing inspection UVs and on CMRS requirements report. In early stage various solutions were analysed – four wheeled, four tracked and four mixed (fig. 2.1.1-2.1.3).

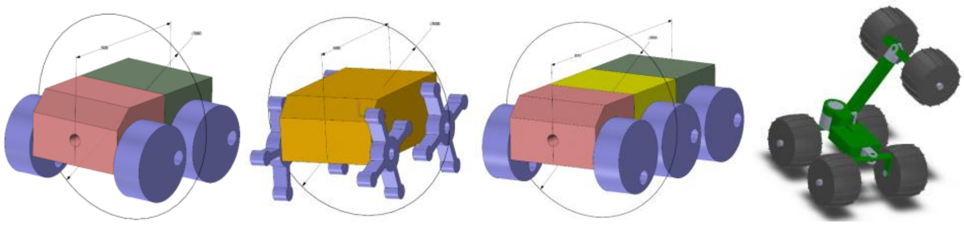


Fig. 2.1.1. Wheeled concepts

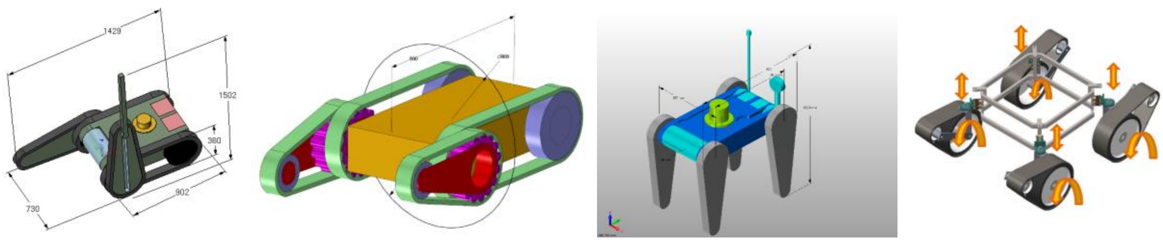


Fig. 2.1.2. Tracked concepts

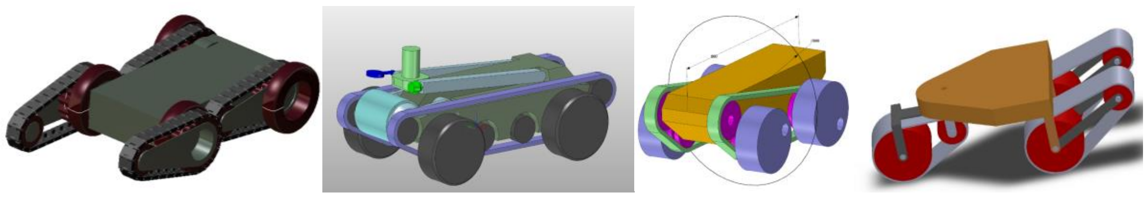


Fig. 2.1.3. Mixed, wheeled-tracked concepts.

The next task was choosing an optimal concept. After a few multibody analyses of the mobility of each concept the designers chose the optimal design. The following criteria were used: Stability while driving through obstacles (without vibrations); Low power consumption; Ability to overcome obstacles higher as the radius of the wheel but lower than the diameter of the wheel; Ability to lift up; Compact construction; Simplicity of a mechanical system; Simplicity of a control system; Maximum volume width of the hull; Overcoming of coal mine longwall system.

The optimization was performed among the group of designers of the UV. They assigned weights of each criterium and gave marks to each concept. In the optimization the best solution became a concept with four adjustable tracks. In the opinion of designers, it has the best ability to overcome obstacles and to lift up relative to the volume of the hull, which resulted in choosing this concept as the optimal one.

After choosing the optimal concept the designers started to test functionality and mobility of this platform in a virtual coal mine's environment (fig. 2.1.4). After this the functionality simulations were tested such as drive stability, cameras types and placement, LIDAR placement and the way of driving the robot.

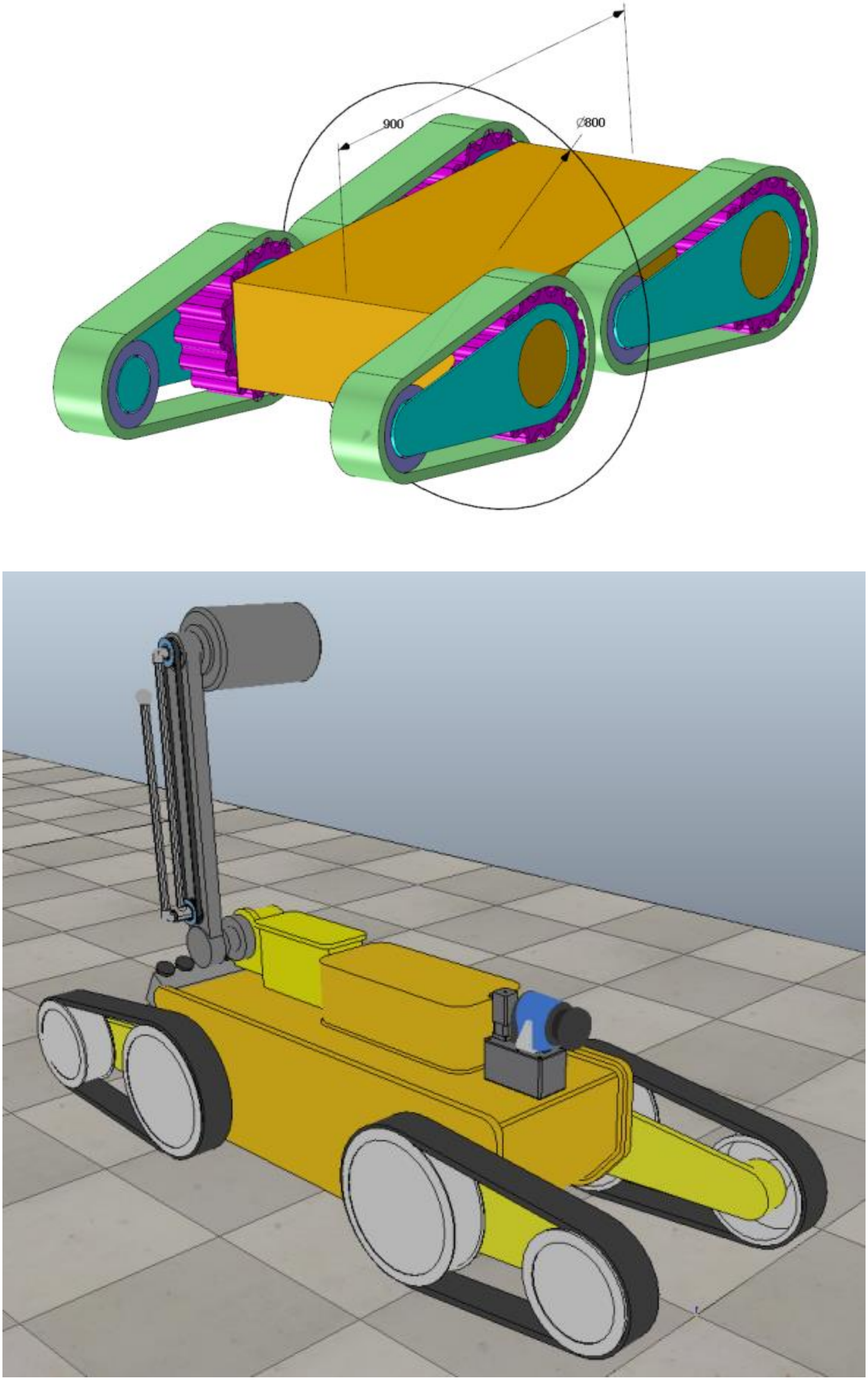


Fig. 2.1.4. Selected concept and the developed version of the concept during simulation in V-REP.

Moreover, there were prepared many FEM analyses and then modifications (if required) to eliminate high stress and displacement during normal work load, drop test and flameproof test (fig. 2.1.5).

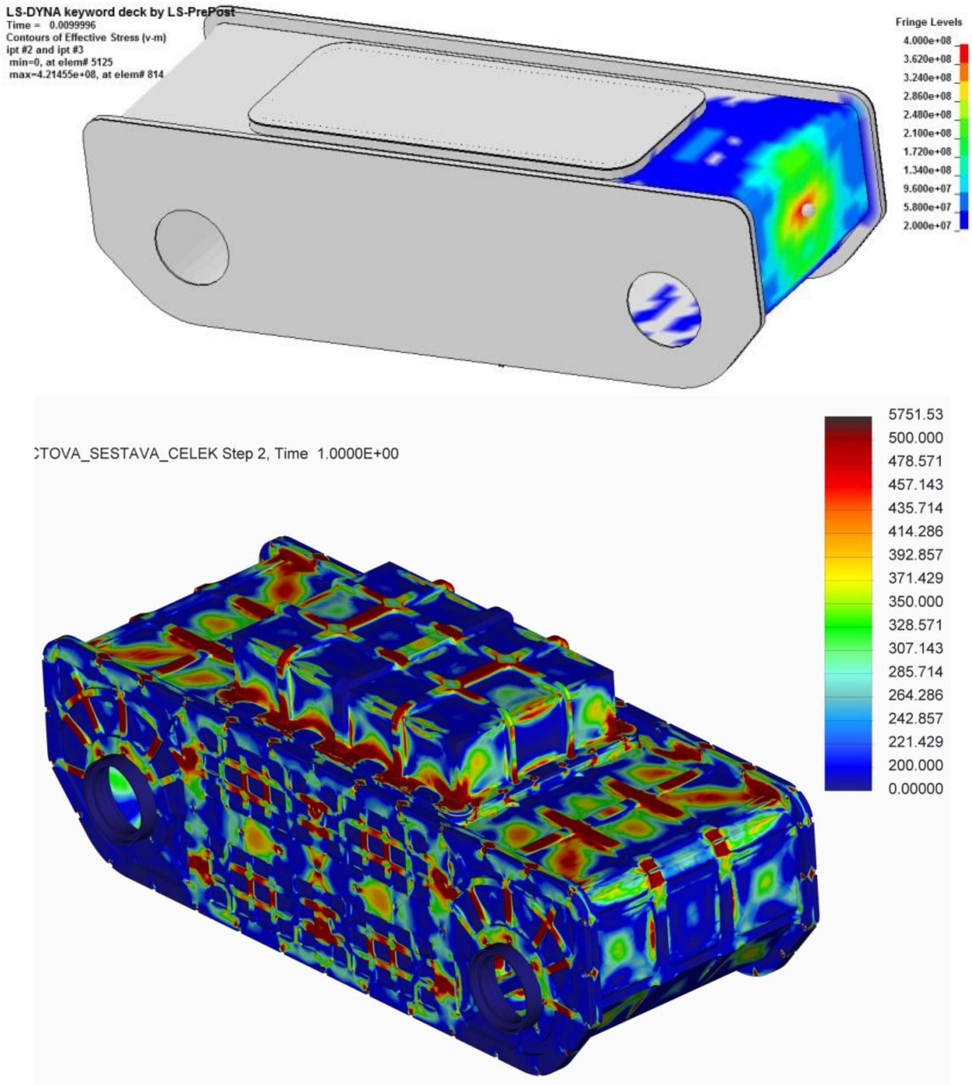


Fig. 2.1.5. A dynamic simulation of drop-test and a simulation of stresses during pressure test for flameproofness.

After gathering all simulations data, calculations, design requirements and layout restrictions, a drivetrain has been designed (fig. 2.1.6). Because motors have to be made according to the ATEX specification, to simplify the design and avoiding additional costs of more than one custom motor, a single motor type was chosen.

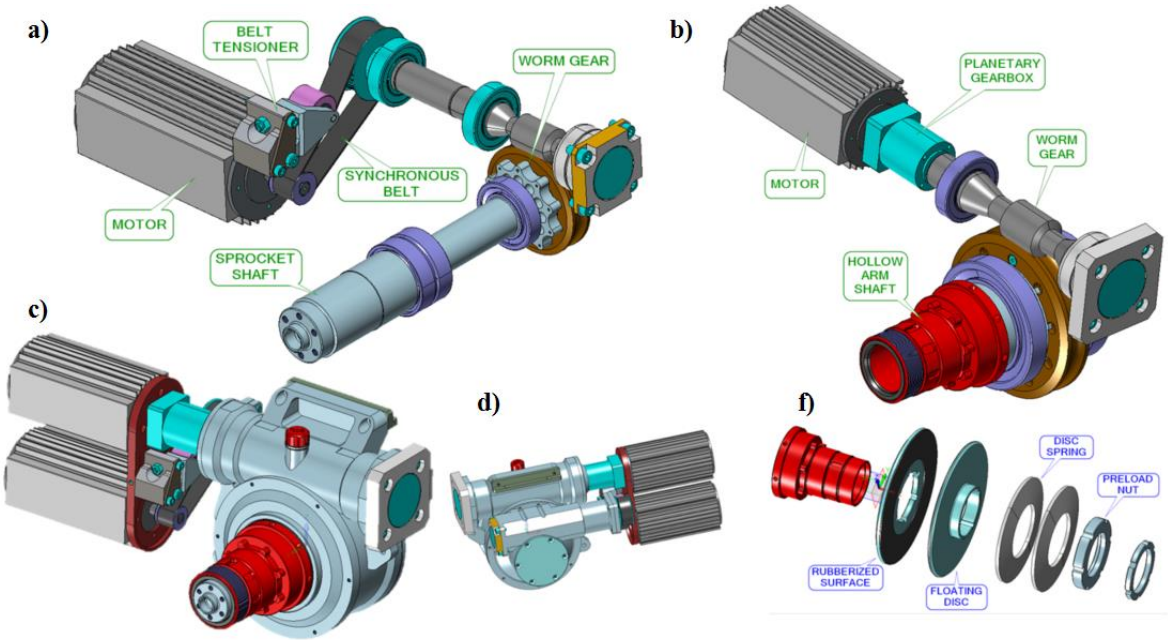


Fig. 2.1.6. Drivetrain components – 3D model and assembled drivetrain units (one left, one right).

Fig. 2.1.6. (cont.) Drivetrain components – 3D model and assembled drivetrain units (one left, one right).

For both the motions – a track and flipper arm - to allow using the same motor type, two gearboxes were designed. For the final stage in the both cases a worm gear was selected. The main advantages of the worm gear are robustness, simplicity and self-locking. The last feature is the most important, as it eliminates the need for an additional brake. One disadvantage of a worm gear is its medium efficiency and the resulting heat generation but since the speed and operational cycle are going to be low, so it won't be a severe problem.

A battery capacity was calculated from the required operational time set in the design objectives and estimated duty cycle. To comply with ATEX standard EN 60079-0 Ni-MH cells were chosen, as they have better energy density than Ni-Cd and Lead Acid cells. They can be found also in the other ATEX-conforming equipment, so that it is a proven solution.

The final mobile platform of UV was manufactured and mounted, as presented on fig. 2.1.7.

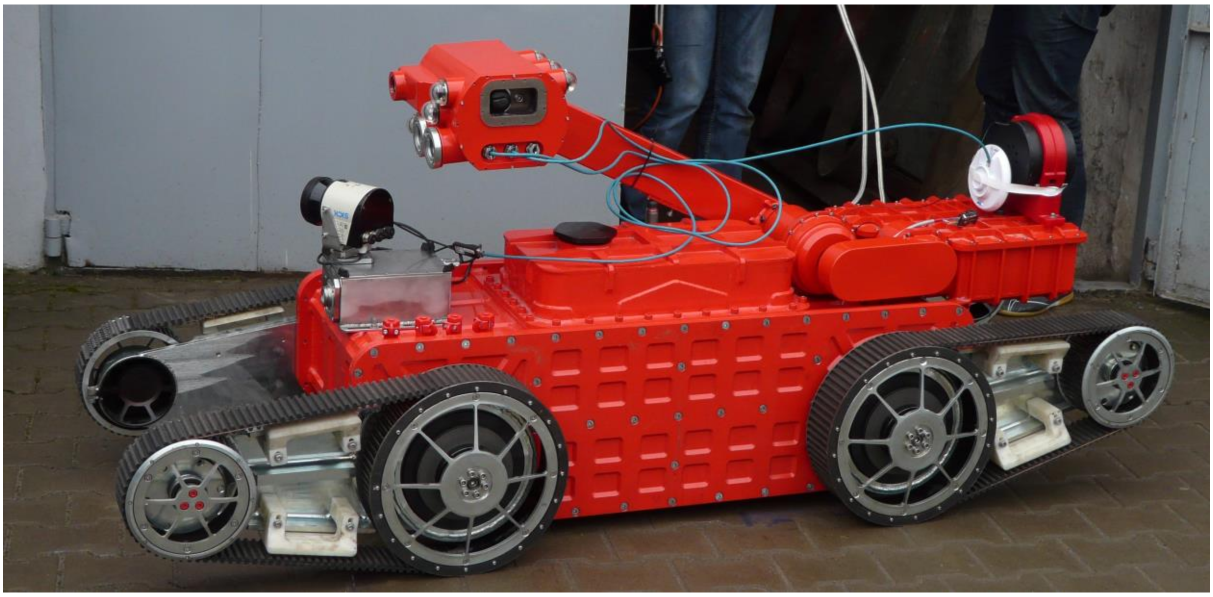


Fig. 2.1.7. Final version of UV platform.

For the mobile platform an additional equipment has been developed. The platform's main external module is an arm with a camera cylinder and a sensor mast (fig. 2.1.8). All the movements of the mechanical system - 3 degrees of freedom (DOF) - are driven by a single BLDC motor, the same as used in the main UV body. The selection of a currently used subsystem of the mechanism – the arm, the cylinder (fig. 2.1.9) or the methane sensors mast - is done by 4 electromagnetic toothed brakes.

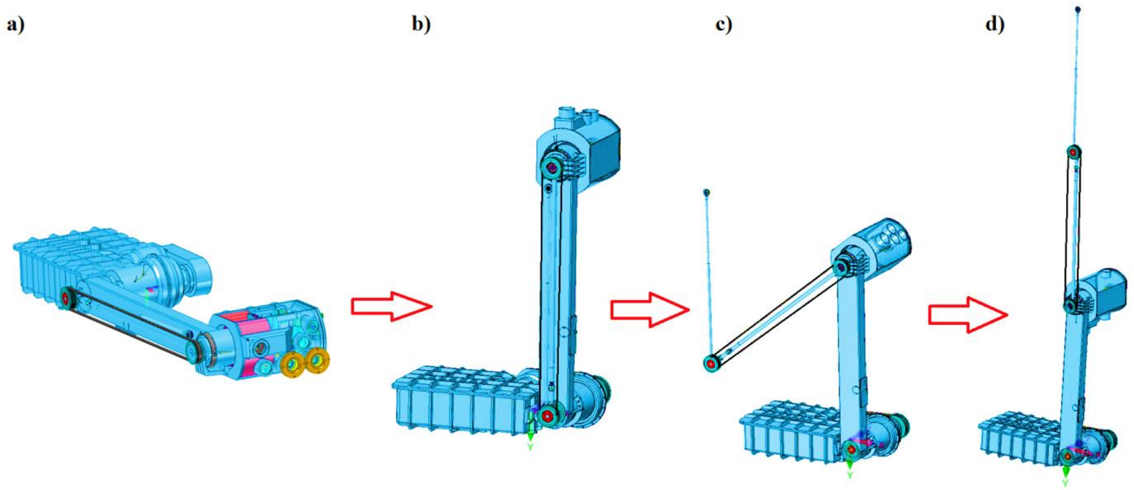


Fig. 2.1.8. 3D model of arm equipped with sensory cylinder and sensor mast.

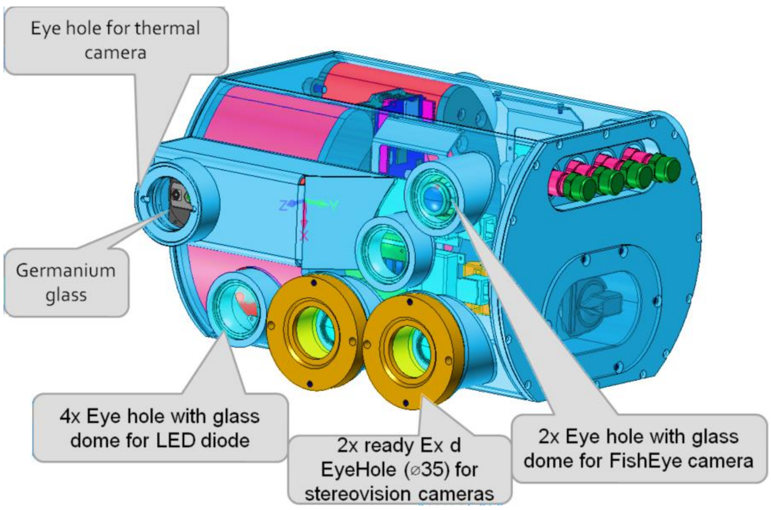


Fig. 2.1.9. Main components of sensory cylinder.

There are also mechatronic modules that are part of the communication system – a fibre reel unwinder and a mote releaser (fig. 2.1.10). The fibre unwinder is just a simple bracket that allows for quick change of the fibre spool. The mote releaser is an automated tray for motes. It can hold up to eight motes and releases them when needed. The motes are hold in place with a rotating latch and when the latch is released they are thrown out with a force produced by a preloaded spring.

Fig. 2.1.10. Left: Prototype of the releasing mechanism. Right: The finished mote releaser with the tray filled with the mote enclosures.

All the described accessories are essential for the full functionality of the platform. Every module has its dedicated mounting point on the main chassis and was designed to work well with the whole system. Fig. 2.1.11 shows the complete robot with all the accessories.

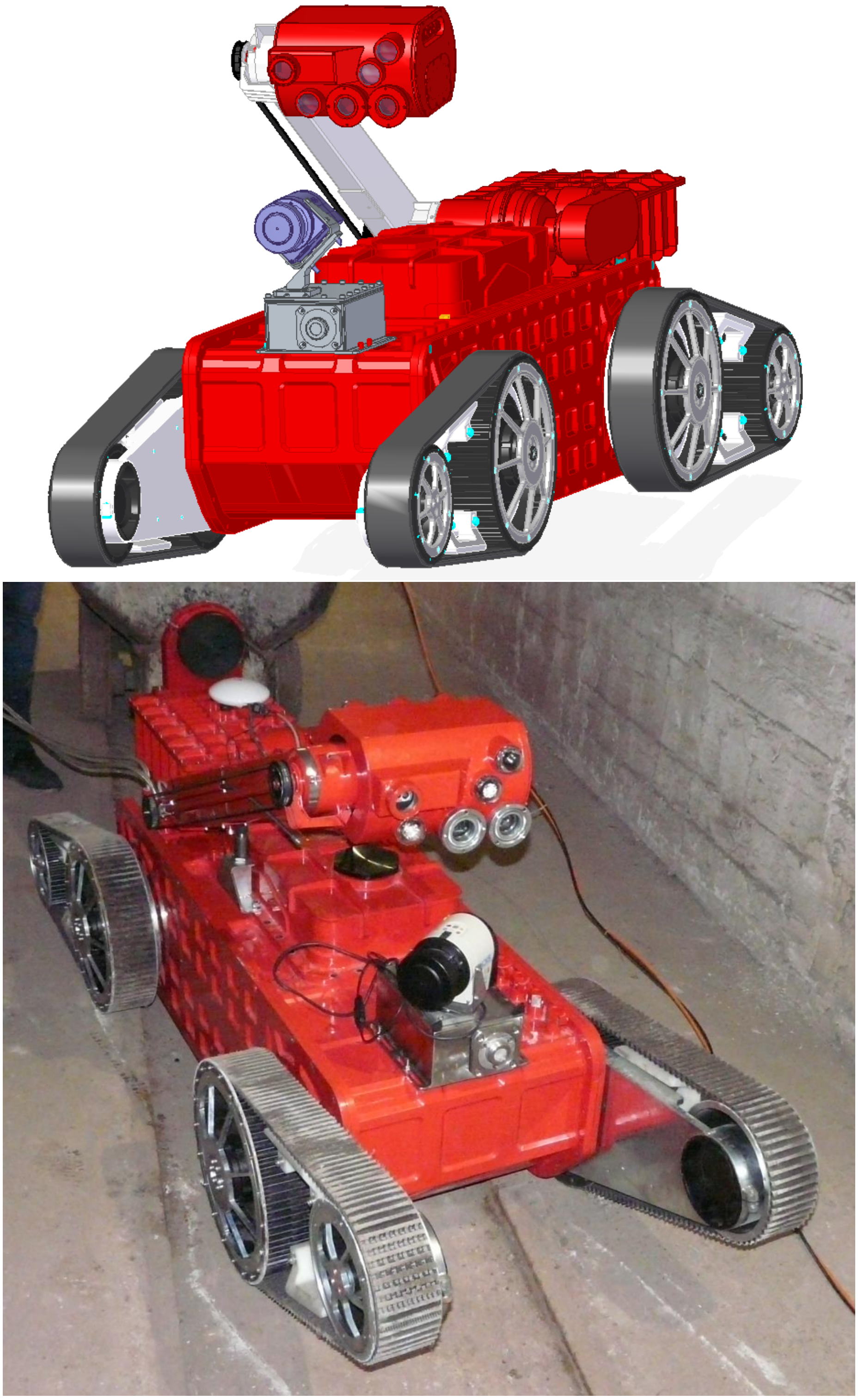


Fig. 2.1.11. 3D virtual model of finished platform and a physical prototype.

T2.2. Research into the communication system and sensory system;

For a mobile platform of the UV three important systems were developed:
1) A communication system;
2) A vision system;
3) A sensory system.

A general scheme of these systems is shown in fig. 2.2.1.

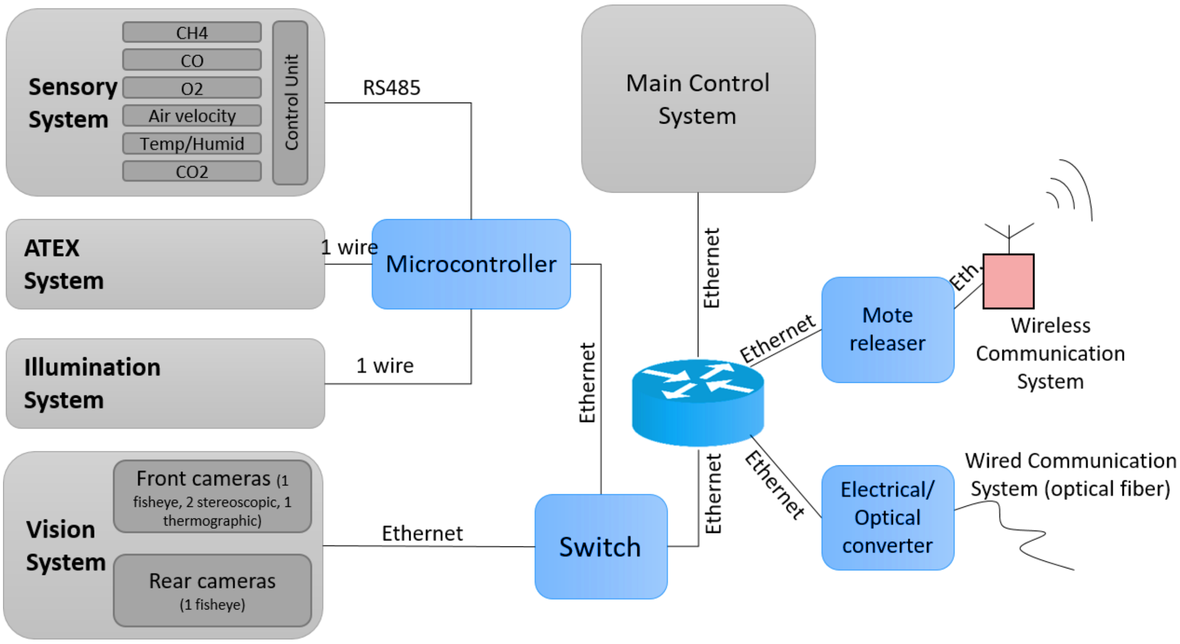


Fig. 2.2.1 TeleRescuer communication connections scheme.

The communication system is divided into two subsystems: the wired and wireless one, while the latter is used as an alternative to the wired one in some cases). For the wired system a 100BASE-FX optical fiber was selected to operate as the main communication link in the system. Bidirectional transceivers are employed in Ethernet-to-Optical converters at both the sides to allow using only one fiber for transmission in both the directions. The optical fiber unwinds when the robot advances. To reduce the risk of a cable damage, the optical fiber spool is installed at the robot side. This spool is shown in fig. 2.2.2.

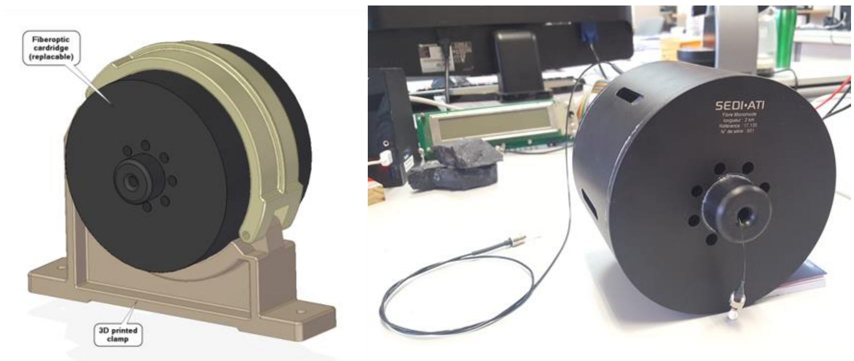


Fig. 2.2.2 Optical fiber spool for real use

The wireless system is composed of several wireless motes that relay the data flows. These wireless motes are released while the robot moves on, and they form an ad-hoc network. The robot informs the operator about the link performance measurements, and it sends messages when the operator must send a command to release a mote. Software and hardware developments were made, and a prototype of the wireless communication system can be seen in fig. 2.2.3.

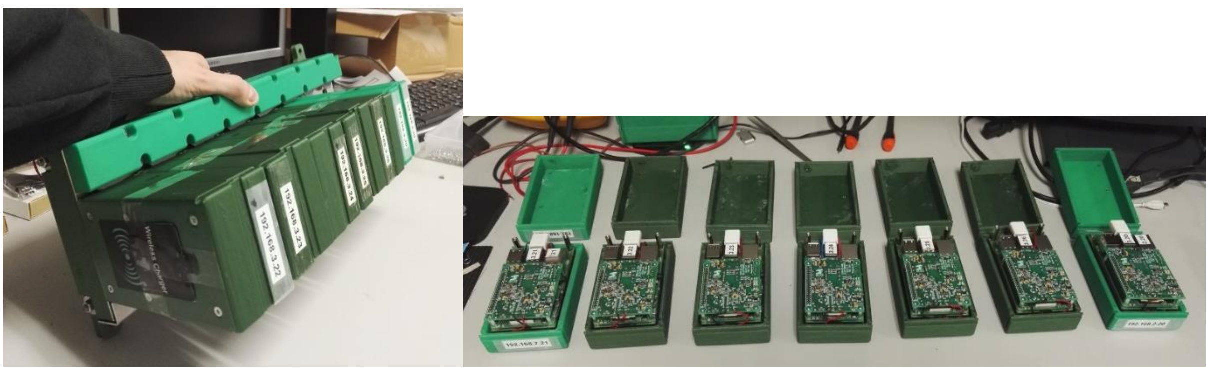


Fig. 2.2.3 Real prototype of the wireless mote dispenser.

The robot vision system is composed of thermal (IR) and standard vision cameras. The thermal cameras are useful to visualize relative differences in temperatures between objects, and when properly calibrated, absolute temperatures too. We have included five different cameras in the visual system, one thermal camera and four standard ones. The thermal and three of the standard cameras are pointing forward while one is pointing backwards, to allow maneuvering the robot in narrow places and omit obstacles. Besides, two of the three front cameras are linked together in a stereo pair so that the operator can have a better feeling of the scene depth by using 3D glasses and displays.

The available bandwidth of the communication system may vary drastically while switching between optical fiber and wireless communications, so that the cameras need to deal with these changes accordingly. We employ H264 encoding for the live feed (stream) and vary the resolution, frame rate and quality of the encoding step in order to accommodate the final bit rate to the communications channel. In order to minimize the delay caused by the cameras, H264 hardware encoding is used (the encoding is part of the process more computationally intensive). The latency of the video live signal through a wired closed network communication is 80-100 msec, including the H264 decoding and display refresh rate of the operator display hardware. Finally, the robot vision system includes a variable intensity illumination setup composed of 4 light-emitting diodes (LEDs) emitting in the standard visual spectrum. One of them is pointing backward and the rest are set at the front. Two of the LEDs are isotropic and the rest use a collimator that concentrates the light in a 6-10º arc in the front of the UV.
The prototype of the vision system integrated in the robot is shown in fig. 2.2.4.

Fig. 2.2.4 Vision system. Left side: Rear part of the robot cylinder (1 LED and 1 fish-eye camera). Right side: Front part of the robot cylinder (1 LED w/ collimator, 1 LED w/o collimator, 1 fish-eye camera, 1 thermographical camera and 1 stereo-pair camera).

In order to measure the environmental status, the robot contains sensors for different gases situated at different levels:

- at the ceil level (3 m): methane (CH_4);
- at the human's face level (1.8 m approx.): carbon monoxide (CO), oxygen (O_2), air velocity, humidity and temperature;
- at the ground level: carbon dioxide (CO_2).

The sensor board is an ATEX-compliant device, which is in charge of measuring ambient gas levels of CH_4, CO, CO_2, O_2, temperature, humidity and air flow. It is connected with the sensor control unit through 13 wires. Fig. 2.2.5 represents real images of the sensor board.

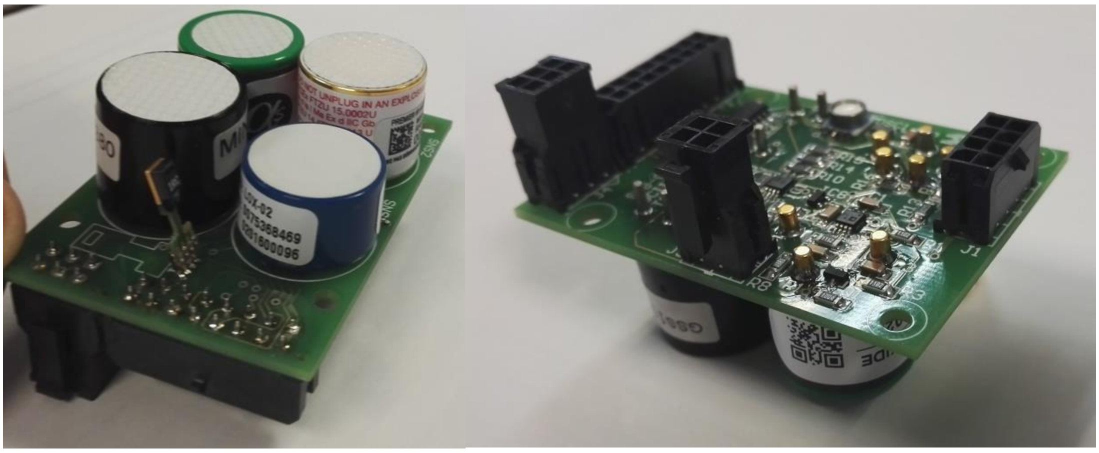


Fig. 2.2.5 Top (left side) and bottom (right side) views of sensor board.

The devices satisfy ATEX requirements to allow their use in coal mines.
Exposed devices are ATEX-M1 compliant, and those that are not, they are ATEX-M1 compliant because they comply with the following two protection modes:

- The first one is the flameproof enclosure in which they are contained;
- The second one is the developed Methane protection system (MPS) (fig. 2.2.6). It cuts off all the power in case of the concentration of firedamp (CH_4, methane) is above the 20% of the Lower Explosivity Level (LEL) of air-methane mixes. The gas safety monitor measures the concentration of firedamp (CH_4) inside the corresponding flameproof enclosure. If such a level is exceeded, the corresponding relays become open.

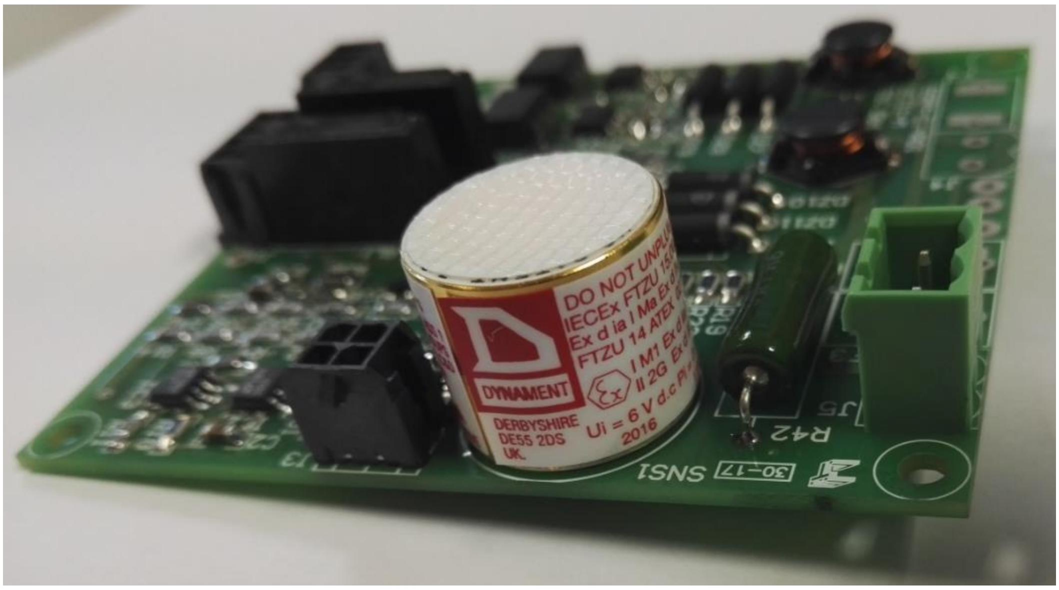


Fig. 2.2.6 Real picture of top side of the MPS PCB.

T2.3. Research into the control system;

The Main Control System (MCS) (fig. 2.3.1, fig 2.3.2) is based upon an industrial PC board with an ultra-low-power CPU (TPD 4.5W), 4GB memory and 512GB SSD HDD, with the Ubuntu Linux operating system. This main board is connected to the especially designed daughter board, which provides easy connection to other subsystems of the mobile robot.

ATEX compliance safety is ensured by several approaches:

- The main security element is a flameproof enclosure of the whole body robot. Whole electronics related do MCS is situated in this containment.
- The next level of protection is an encapsulation of electronics components of MCS by a special compound (LUKOPREN N 6681).
- In this encapsulation are deployed several thermo-fuses for cutting off the power in case of increased thermal exposition from any internal parts.
- The last related protection is the main fuse for the internal components failure prevention.

The interface board (daughter board) between the CPU board and other robot systems is equipped with the 32bit microcontroller from STMicroelectronics which allows adding some advanced functionality to this board. This MCU is running at 168MHz. There is also installed the possibility to use a backup battery and a switch for BOOT option selecting. Via an ADC terminal block it is possible to connect an analog signal from the methane sensor. This provides information about the methane concentration level.

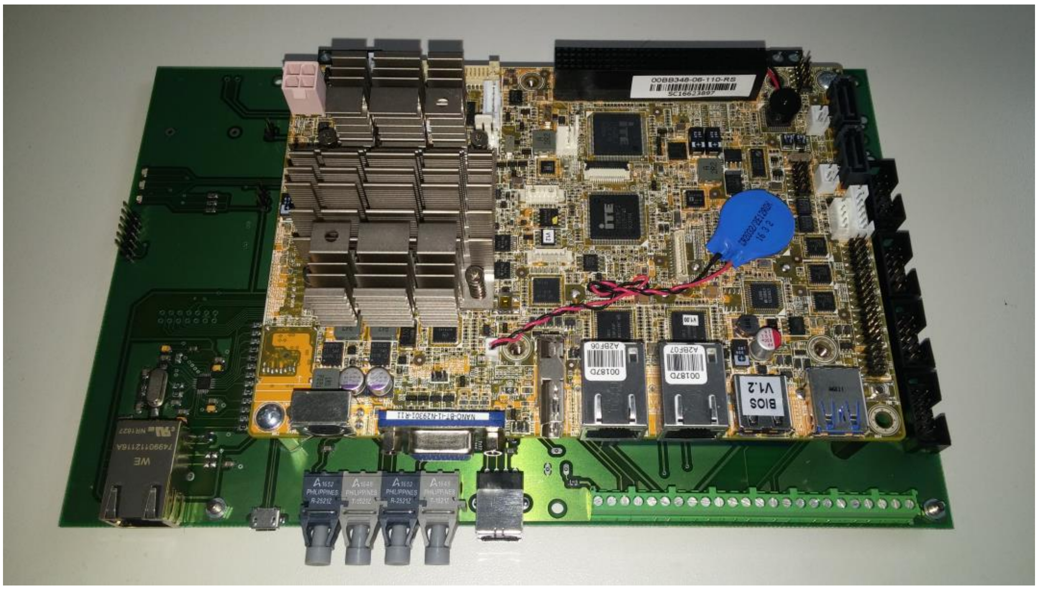


Fig. 2.3.1 Overview of the Main control system board

The main purpose of the interface board is to provide communication capabilities for the PC board used. This function is realized by four RS232 lines connecting the PC board and the interface board. RS232 signal is adapted to a level suitable for connecting to the microcontroller. There are two identical converters on the interface board, each of them for two RS232 lines.

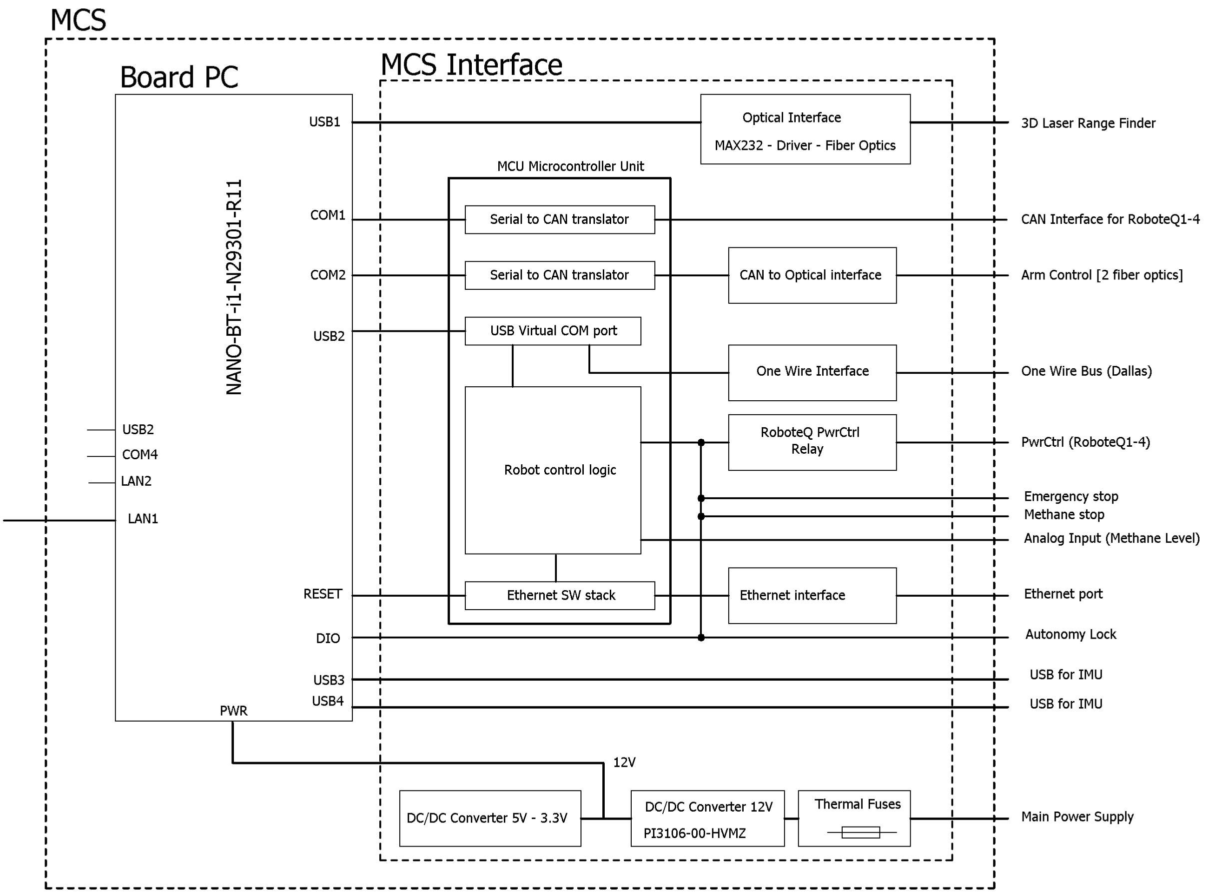


Fig. 2.3.2. Main control system – block diagram

MCS module is powered from the main battery. The Absolute Maximum Input voltage is 63V. The Power source unit is designed as a cascade of three voltage regulators for the internal microcontroller (MCU) powering. 12V is also used for powering the connected PC board. For safety and research results is possible to measure current used by MCU.

The next communication interface is USB connection directly to MCU. This interface is secured by Electrostatic discharge (ESD) protection device. This communication line is designed for future use (reserve). For the communication with four motor drivers (RoboteQ) the CAN bus is used. This bus is managed by CAN interface at the microcontroller at the interface board. A part of its firmware provides translation between one of RS232 interfaces and the CAN bus. For the communication with the arm's motor controller (located at the external box) an optical fiber is used. The interface between CAN signal from the MCU and this optical fiber is realized by a module which is based on HFBR optical devices (transmitter and receiver).
For the communication with an external 3D laser range finder optical fibers are used, too. The interface between the CAN signal from the MCU and this optical fiber is realized by a module shown in the figure presented below.

An important task of the Main Control System is to secure extra safety for the motion control system. This is done by an independent safe control of the motors' controllers (RoboteQ). These signals are driven by SF4D relay with forcibly guided double contacts. The relay complies with EN 50205, Type B and with IEC/EN 60335-1 (GWT). All the motor drivers PwrCtrl inputs are driven simultaneously and can be controlled from these sources:

- By the user application or directly from PC;
- By the external methane sensor;
- By the central stop push-button.

The software of the Main Control System is running on the industrial single board computer based on the PC nano board (fig. 2.3.3).

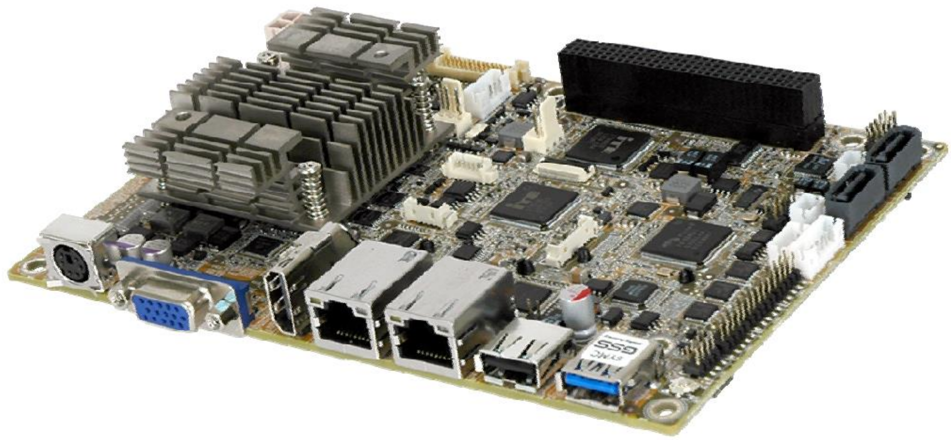


Fig. 2.3.3 PC board – NANO-BT

T2.4. Development of methodologies for building maps

One of aims of the the Telerescuer is the possibility to detect obstacles in the working environment and to measure distances from these obstacles. The developed Laser Scanner is able to detect obstacles not only in a plane, but also in 3D environment. This ability enables the operator to fully control the robot in any complicated environment even under a bad lighting condition or in a dark environment.

The 3D Laser Scanner is mounted on the front of the Telerescuer on its top to have the best conditions to measure distances from obstacles around. The communication with the Main Control System (MCS) is realized by the pair of plastic optic fibre. The power supply is provided from its own batteries.

The 3D Laser Scanner prototype introduced in previous annual reports was completely tested. All the implemented parts were working well and cooperated together in expected manner. Basing on the tested prototype the final 3D Laser Scanner unit was made.

The developed laser scanner is shown in fig 2.4.1.

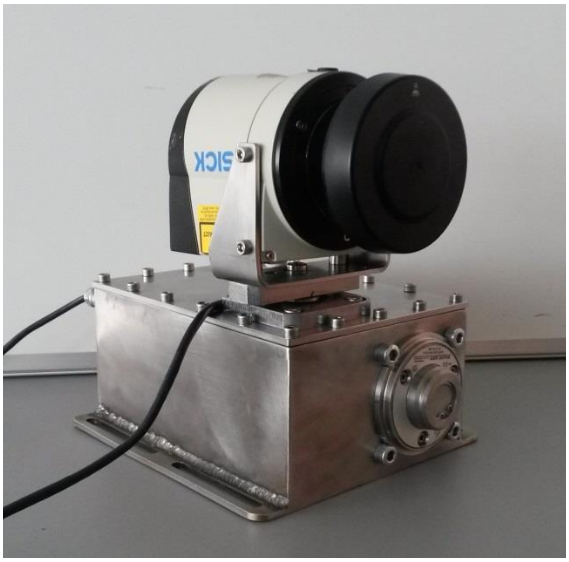
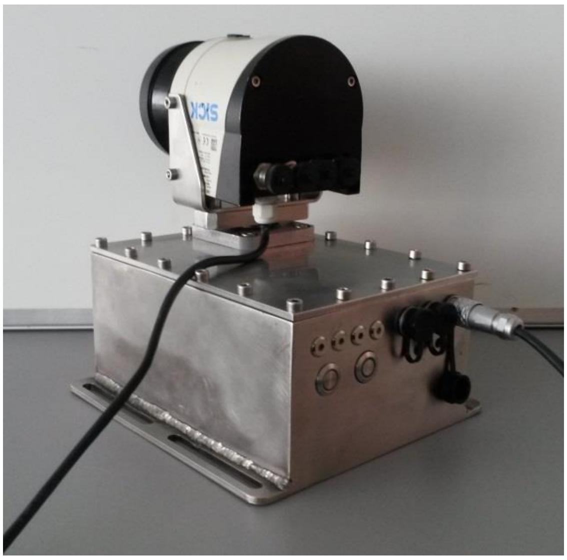



Fig. 2.4.1 The 3D Laser Scanner for the Telerescuer

The main case is from stainless steel. The base (pan) is welded. On the lid on the top is mounted the laser range finder LMS111. The laser scanner rotary mounting is shown in more detailed construction drawings in separated documentation. For the Atex "S" compliance the methane sensor SC-CH4 was added. In the previous figure it is visible on the front side of the metal case in left figure.

A methodology for point cloud registration was designed and tested on data captured in the mine Queen Luiza in Zabrze (Poland). An average number of points in a single cloud is about 200 thousands points. The clouds themselves were made in an approximate distance 2 m from each other in one direction of the shaft. During gathering the data for clouds it was also gathered data of the tilt of the scanner.

To merge points cloud the Point Cloud Library (PCL) is used. This library implements a few algorithms for point clouds registration. The algorithm with the best result is the iterative closest point. For the mine corridor it is possible to correctly register neighbouring point clouds taking advantage of additional data from odometry and data from the position sensor of the laser scanner.

The only one problem of registration was detected by acquiring point clouds at an intersection of corridors. The ICP algorithm did not correctly register two point clouds at the entrance of the intersection. The problem is visible in fig 2.4.2. There are two neighbouring point clouds captured at the distance 2 m. The first one is white and the second red. The ICP algorithm was not able to register correctly point clouds captured at the edge of the corridors intersection. The differences in point clouds are too big and the second points cloud is turned slightly.

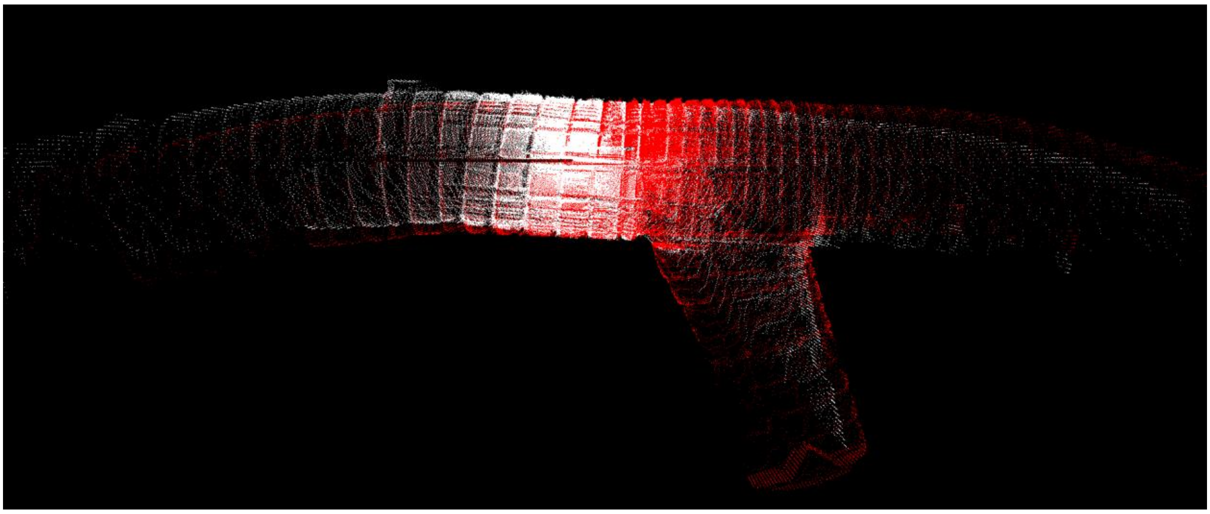


Fig. 2.4.2 ICP algorithm does not correctly register two point clouds at intersection

The following research and testing showed that the easiest solution is to capture point clouds more often at all intersections. The testing proved that the capturing of point clouds at intersections is necessary in the distance of 1 m. The result of three point clouds registered at the edge of the intersection is shown in fig 2.4.3.

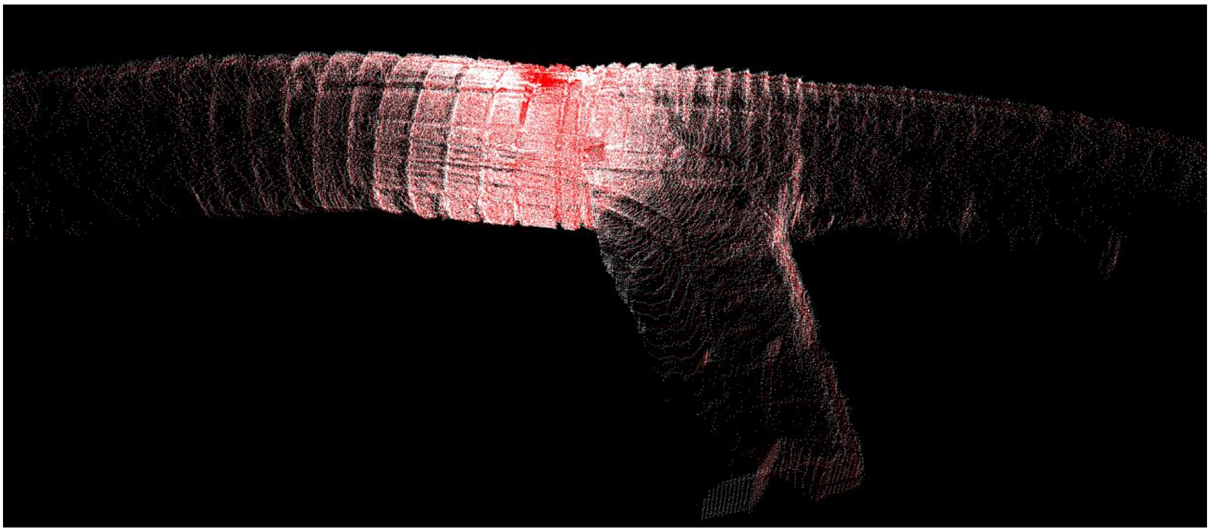


Fig. 2.4.3 Point clouds captured in the distance of 1 m and registered correctly

To summarize a system for map building on the base of 3D scans it is necessary to say that results are more than satisfactory. Data delivered to the operator on the base of scans can be used in many critical situations, and shows detailed state of the environment around the UV (fig. 2.4.4).

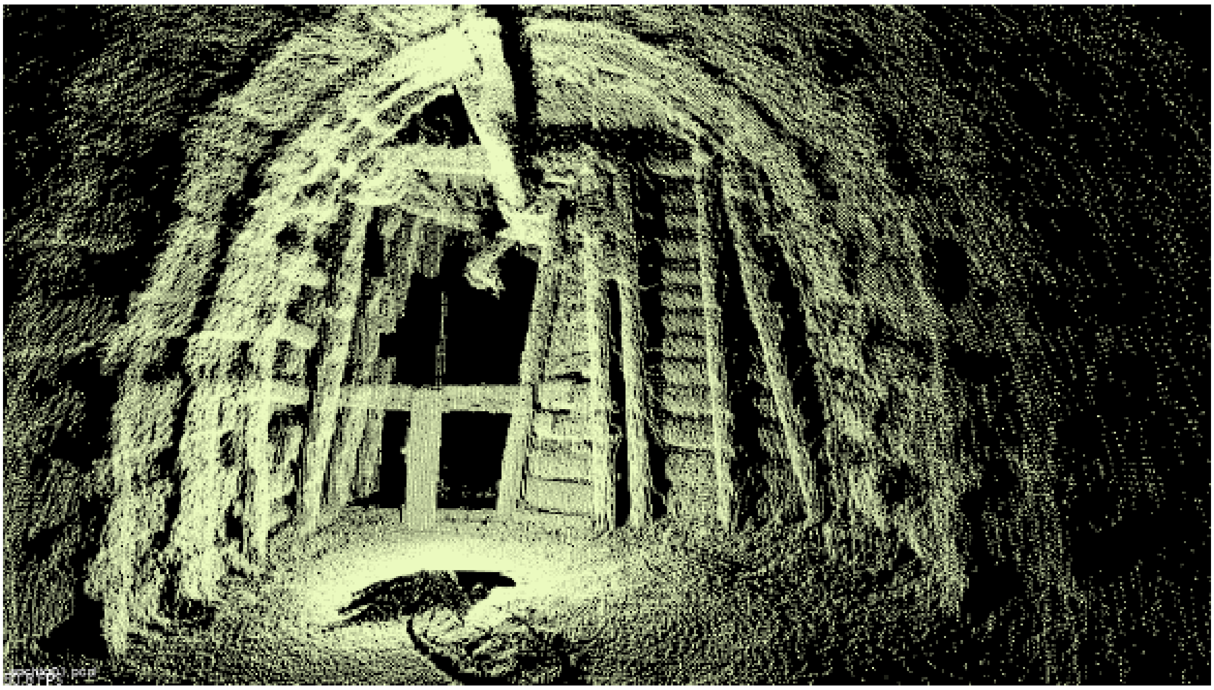


Fig. 2.4.4 Point clouds captured as a single scan

T2.5. Research on methods of autonomous operation of UV in a known environment

A system of autonomous operation consists of several main subsystems, i.e. localization, autonomous movement control and map building, path recording, autonomous return subsystems. They are briefly described below.

The localization subsystem is responsible for calculating the TeleRescuer's current position and orientation. It is used by two other subsystems: the scanner subsystem and the autonomous movement subsystem. The scanner subsystem (which acquires and matches the scanner point clouds) uses localization information as an initial information when performing clouds matching. The autonomous movement subsystem requires position and orientation information for correct path finding. Localization information is also shown to the operator by the operator interface.

Internally the localization subsystem is based on three different types of information (fig. 2.5.1). The first is rotary encoders data, which communicate how many rotations the robot wheels have performed. Given that the position between wheels is constant we can calculate the path by approximating it by a circle. It allows us to calculate both the changes in orientation and in position.

Another source of information is AHRS (attitude and heading reference system), commonly referred to as IMU (inertial measurement unit). It provides information about the current orientation and accelerations. This does not allow to correctly calculate distance travelled, but can be used as part in later fusion process.

The last source is point cloud matching. Even though the scanner subsystem uses rough pose estimation as its input data, it is still possible to get the position and attitude corrections to improve the localization reading after every scan.

The localization subsystem workflow is as follows. The rotary encoders data is transformed to the position and orientation data. These and IMU data are fed into an EKF filter (Extended Kalman Filter), which performs data fusion to give us the current attitude and position. Additionally, whenever a scanner point cloud matching correction is available, it is also fed into EKF as an additional source of information.

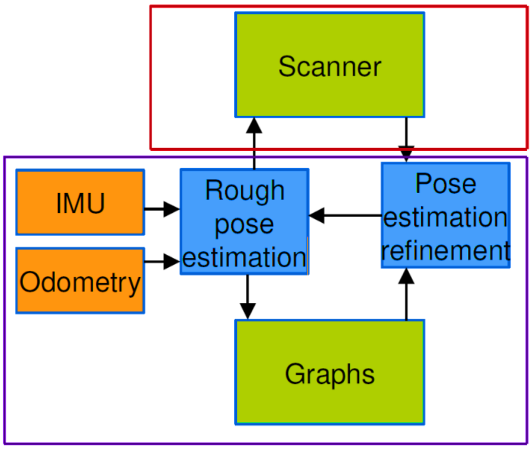


Fig. 2.5.1. Data fusion workflow

An autonomous movement control subsystem's main purpose is to allow for certain autonomous metabehaviors: returning to the starting point and moving to the goal given. Internally autonomous behaviors are based on a set of simple behaviors, which then combined together allow the vehicle to perform certain actions (moving and rotating). Each behavior on every algorithm iteration gives us a vector, that shows us the direction and magnitude (speed) where the robot wants to go.

Behaviors can be divided into three main groups:

- Follow group - follow behaviors simulate goals that we want to reach. There are the following behaviors in this group: move to a point (straight), turn right and turn left.
- Avoid group – the main purpose is to not collide with any objects in the path of the Telerescuer. This set of behaviors is in a way the most important subgroup – it is preferable for the autonomous movement subsystem to stop working than to risk collision and damaging both the robot and an object the robot collides with. These behaviors try to go away from objects in certain areas – in the front of the robot and at the sides. Also there is a behavior which allows maneuvering around obstacles in front of the robot, by adding a vector perpendicular (to the avoidance vector) to the obstacle itself.
- Random group - these behaviors consist of low and high frequency noise. These random elements allow to resolve situation, when all the possible choices are of equal priority. For example, imagine that the robot is in a front of an ideal wall and it wants to go around it. Without a random vector the autonomous movement subsystem will be unable to make a choice, because going both left and right has the same priority.

The robot during the operation moves along the coal mine galleries. Thus, in successive time period, it may be located in different unique places. So that, it is possible to build the map of places in which the robot was located during the movement. A proved concept of this approach is shown in fig. 2.5.2. It assumes, that after the recognition of the unique place, this one is added to the map, with information about the distance to the previous unique place and information about the possible neighbours (other unique places) and ways to move from current unique place. The map of the coal mine galleries, which is used during autonomous return, is represented as a graph. Information concerning nodes and connections between them is stored according to the table presented in fig.2.5.2.a. The created map contains information about subsequent unique places, a value of identification ratio, the robot position and distances between particular places.

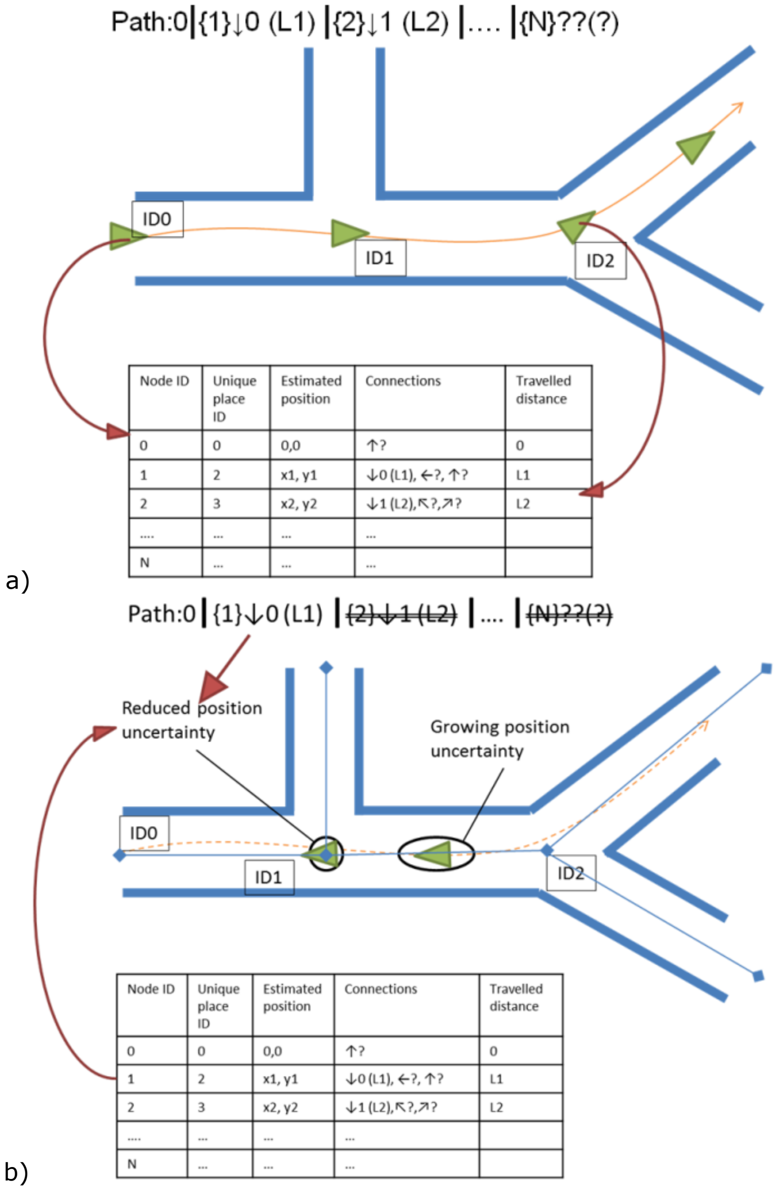


Fig.2.5.2. Algorithm of building a map and autonomous return according to the recorded path

During the movement of the robot in the teleoperation mode the movement path is recorded and stored in such an exemplary pattern *Path:0|{1}↓0 (L1) |{2}↓1 (L2) |…. |{N}??(?)*. When the communication is lost (or on operator's demand) the robot is able to return autonomously according to the recorded path to the starting point or at least to the place where the communication could be restored. When the robot moves back according to the recorded path the uncertainty about its position grows up due to accumulating localization errors which are inherent to the applied inertial and odometry localization methods. Information stored in the recorded map (graph) is used to reduce the localization errors, i.e. when the robot moves back autonomously according to the recorded path and it detects the consecutive unique places, then uncertainty decreases and it (robot) exactly knows where it is located in the coal mine galleries (fig. 2.5.2.b).

The aim of one subtask was to develop a method to identify unique places, in which the robot during the movement in the coal mine sidewalk may be located. The second objective of this task was to develop a method to build the map of unique places, in which the robot is located during all the movements. The task was carried out in a virtual environment using the V-REP software (fig. 2.5.3.a) and the real environment using an additional testing platform (fig. 2.5.3.b) and also the TeleRescuer robot.

From a technical point of view, the process of identifying the unique places comes down to the task of object recognition (unique places) in observed/recorded environment (scene). In the considered case, it was based on the point clouds recorded during the movement of the robot. To develop a necessary algorithm, the selected algorithms and methods contained in the Point Cloud Library were used.

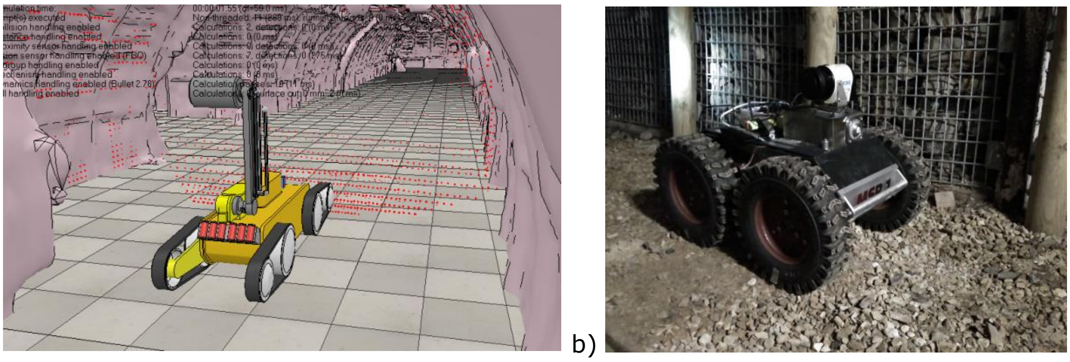
a)  b)

Fig. 2.5.3. Test of the autonomous return module in simulating (a) and real (b) environments

In the general case, the algorithm of identification of the unique places consists of the following steps:

- defining the models of unique places,
- recording the actual point cloud (the so-called scene) during the movement of the robot,
- preliminary processing/filtering of the recorded cloud,
- identification of a unique place on the scene.

In the presented method, each unique place is saved as a cloud of points recorded in the environment in which the robot operates. Depending on the environment, it is possible to define various models of unique places. The most basic of them are: right corridor, left corridor, branch, narrowing, dead end, left corner, right corner, etc. Due to the fact, that the registered point cloud in many cases is very large and includes many irrelevant (from the algorithm point of view) points (noise, reflections etc.), the algorithm carries out few filtering processes.

In order to verify proper operation of the developed algorithm for identifying the unique places and map building, the verification tests were conducted. These tests include building the set of models of unique places and then build a map of the places on the route of the robot movement. The exemplary route is shown in Fig. 2.5.4. The obtained results presenting identification ratios were on a high level of convergence, which means that autonomous operation can be implemented successfully.

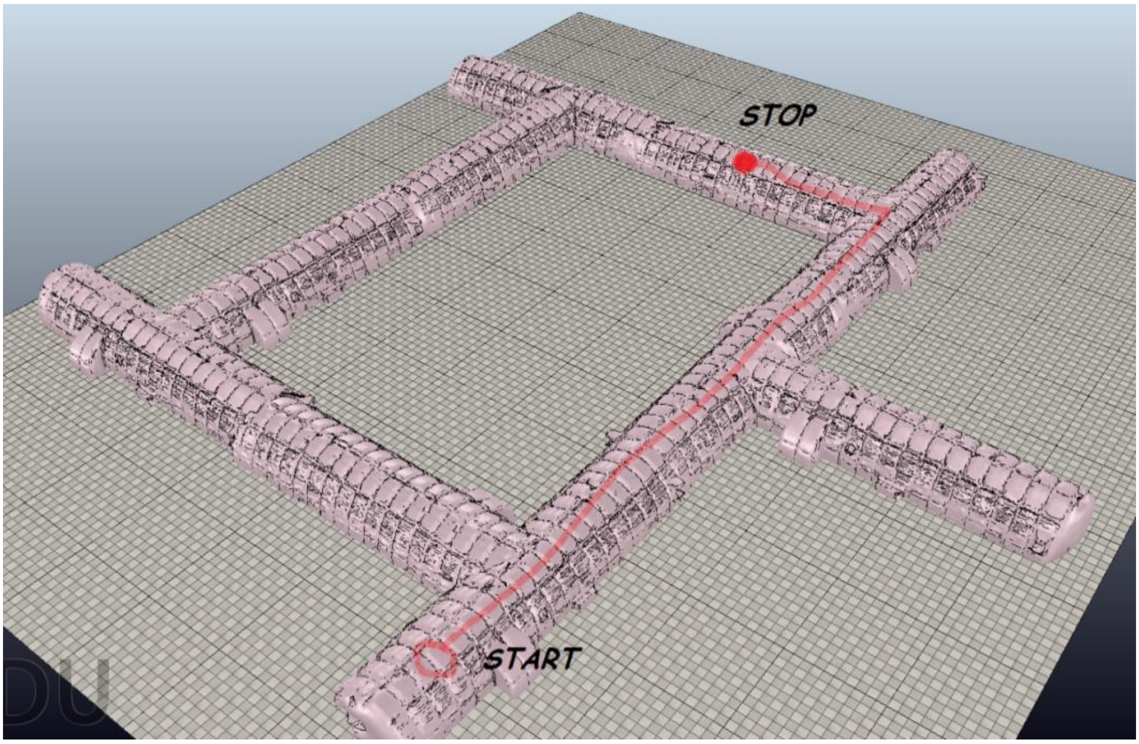


Fig. 2.5.4. Route used in verification analysis

T2.6. System integration

Software of the Telerescuer control system is relatively complex, because the robot contains many subsystems. Software located in the robot body (running on the MCS under Linux Ubuntu) is based on ROS – Robotic Operation System. ROS is an open-source, meta-operating system for robotics systems. It provides services expectable from an operating system, including hardware abstraction, low-level device control, implementation of commonly-used functionality, message-passing between processes, and package management. It also provides tools and libraries for obtaining, building, writing, and running code across multiple computers.

On the diagram in fig. 2.6.1 is presented an architecture of the main control system. The system is logically divided into parts (ROS nodes). Nodes marked by green are responsible for communication with hardware parts of the robot (motor controllers, sensors etc.) Orange nodes are responsible for autonomy behaviour of the mobile robot and 3D map building.

For communication with other parts of the control system (an operator control panel and a software simulator) is responsible the blue-marked node. This software component provides translation of the internal ROS communication between individual nodes to the communication datagram designed at the beginning of this project (based on TCP-IP). The translation is necessary, because the operator system is programmed under Windows, not ROS.

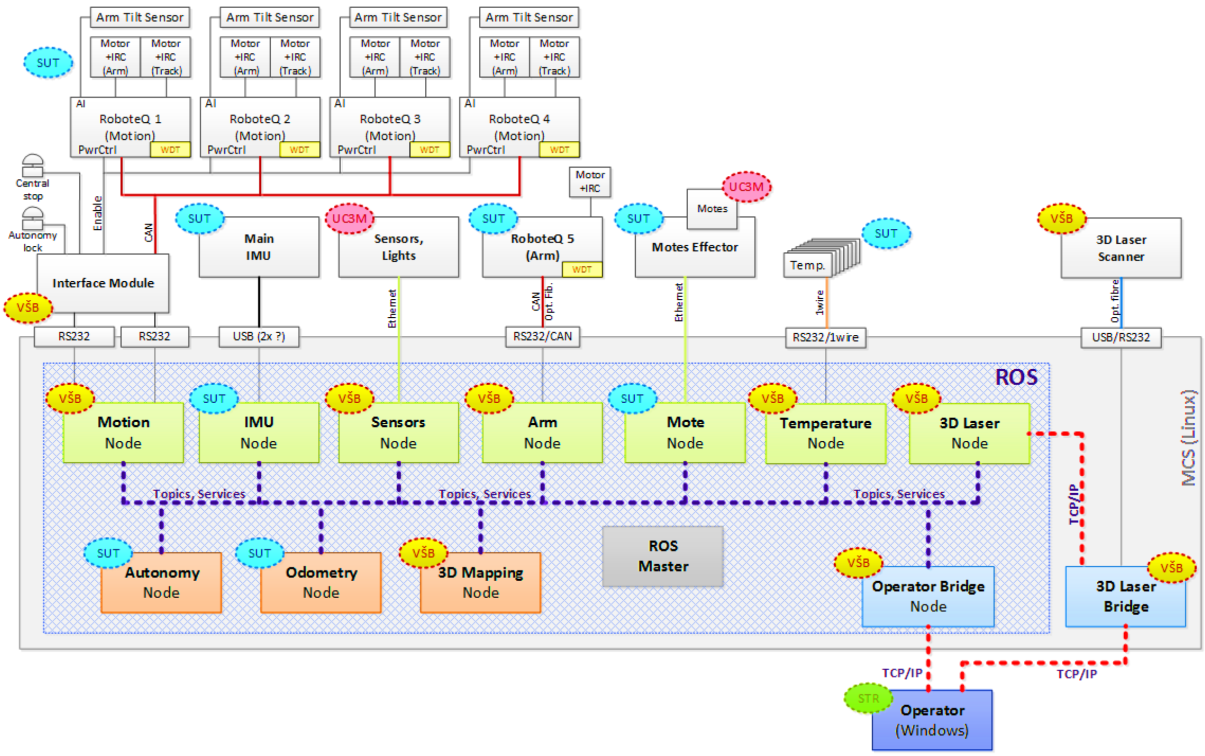


Fig. 2.6.1 Structure of individual subsystems of control system software

Communication between individual subsystems (nodes) inside ROS is done by native ROS communication means, namely:

- Topics – one-way stream of messages established between a publisher and subscriber(s). Any node can register as a subscriber to any topic published by another node and will automatically start getting all the messages on the topic.
- Services – pair of messages (request and reply) exchanged between two nodes. A client node calls a service provided by a server node by sending the request message, the server node processes the request and answers with a reply.

Data and information exchanged between individual subsystems are logically assigned to separate commands. All commands have two versions – a TCP/IP command used in communication with the operator station and equivalent ROS Topic or Service. Most commands include some data, some commands also have a related reply with its own data.

The control system of the mobile robot Telerescuer (MCU – Main Control Unit) is based on an industrial PC board with a small footprint – format NanoITX. This board is encapsulated in a special box with modules for optical communication and a module with the Inertial Measurement Unit (IMU)

and it is placed in a flame-proof enclosure “d”. This way, the double explosion-proof safety required for M1 category group I is arranged.
Eight EC motors (4 for track motion of each tracked arm and 4 for rotation of these arms) provide movement of the mobile robot. These motors are driven by four dual-channels RoboteQ motor drivers connected to the MCU by CAN bus. Each driver has independent battery pack with common ground.

All subsystems are interconnected by an optical fibre or intrinsically safe metallic connections. CAN bus communication lines with metallic wires are used to control the motion subsystem motor controllers. Another CAN bus is realised by the optical fibre and is designed to provide communication with one motor controller located in the sensory arm. Communication with the 3D laser scanner is arranged by a bidirectional optical fibre link connected to an RS232 interface.

The MCS is also responsible for communication with 28 thermometers located in some important parts of the robot chassis to provide an online measurement of thermal conditions of motors and gearboxes.

There are two independent subsystems of communication with the operation station. The first one is optical communication by optical fibre (solution by Sedi-Ati company). Secondary (backup) communication channel is the wireless communication with a lower speed than through the optical fibre, with a pack of releasable wireless repeater stations (motes).

2.2.3 Research into virtual teleportation technology and development of a simulator

Within a workpackage **WP3 Research into virtual teleportation technology and development of a training simulator** the following tasks were realised:

- Development of the concept of a methodology and system for virtual teleportation;
- Research into knowledge representation;
- Development of a knowledge-based methodology of virtual immersion;
- Prototyping software and hardware of the human-machine interface;
- Virtual teleportation technology integration;
- Prototyping 2D/3D visual hardware/software system for training simulator;
- Development of methods for realistic simulations;
- Prototyping human-to-machine interface for training simulator;
- Training simulator software development, system integration and extensive testing.

T3.1. Development of the concept of a methodology and system for virtual teleportation;

One of the key elements of the TeleRescuer project is the ability to obtain virtual teleportation of the rescuer into the sub terrain areas (e.g. areas of mine) that are affected by a harmful event. The purpose of virtual teleportation is to obtain perception of presence in virtually recreated representation of the real world. In this case the rescuer, who is responsible for controlling the robot movements, shall be able to obtain such a state of virtual immersion. As a result of virtual teleportation, the operator should be able to achieve better orientation in the robot’s surrounding than a person who is equipped with classical means of presentation of information obtained by the robot. It will allow for rapid recognition of conditions prevailing at the surveyed area, as well as to obtain ability of precise control of the robot’s movements. Reaching such a state requires precise corroboration between devices mounted on the robot and the operator station, as well as utilization of specialized equipment and techniques which will allow for proper stimulation of human senses.

Among many human’s senses, which can influence the ability to obtain the state of virtual immersion by the rescuer, the most important are vision, hearing and touch. In the area of vision sense stimulation, a review was done of methods for visual data acquisition (various configuration and types of cameras that can be installed on the robot), as well as techniques for data visualisation (such as 3D cave, head mounted displays, 2D / 3D screens projectors, lenticular displays etc.). Methods that were selected for the review within this task allow to obtain various degrees of virtual immersion by the operator.

For the auditory stimulus an analysis of a system of sound data acquisition and location of receivers on the robot’s body as well as a review of methods for sound reproduction were done. Similarly, for tactile stimulus various methods were taken into consideration such as the force feedback at the level of the controllers, 6 DOF platforms utilization etc.

The robot created during the TeleRescuer project is characterized by high level of DOF movement, thus in order to operate it efficiently proper controllers are required. Therefore, within this task an analysis of possible equipment for the robot actions control was conducted.

Data that was obtained during this phase was part of deliverable D3.1 A report on rescuers' knowledge acquisition and representation. Results were utilized in the next Tasks 3.2 and 3.3 during consultations with the domain knowledge experts in order to come up with a knowledge-based method of virtual immersion.

T3.2. Research into knowledge representation

In the TeleRescuer project we needed an expert knowledge in order to be able to design, in the proper way, the virtual teleportation-based system specifically designated for rescuers and conduction of robotic-supported rescue actions and mining roadways supervision. The purpose of the system is to introduce precise robot movement controlling abilities as well as to allow the rescuers to quickly acquire skills in the area of the robot operation.

At the initial state of the project the research was done in the area of knowledge acquisition and knowledge representation. Basing on the obtained results we were able to come up with the methodology for domain experts selection and the process for knowledge extraction (e.g. tools such as SurveyMonkey**Błąd! Nie można odnaleźć źródła odwołania.** (fig. 3.2.1. left)) and processing.

As our main domain expert, we choose a person with years of experience, in the area of mining equipment utilized during rescue action conduction, MSc Eng. Piotr Golicz from the Central Mining Rescue Station. In addition, we had an access to other professional mining rescuers employed in CMRS who were employed for the purpose of consultation of the undertaken approach at the early stage of the project development and were also employed during the product validation phase.

In order to obtain domain knowledge, the following techniques were utilized:
- extraction of knowledge from a domain expert by a knowledge engineer,
- extraction of knowledge from a domain expert without presence of knowledge engineers.

We decided to use the first approach for data acquisition from our main domain expert and the latter approach for mass knowledge acquisition from the rest of the rescuers. Consultations with our domain expert took place at CMRS premises.

We discussed with the domain expert about the needs of rescuers, during conduction of rescue actions, in the areas of:
- robot controllers,
- visualisation of the robot environment,
- sensor data visualisation,
- sound acquisition and tactile stimulation.

As results of our talk a vision of the virtual-based teleportation system was obtained, and two surveys were prepared. Then a technique of acquisition of knowledge from a domain expert without the presence of the knowledge engineers was utilized for the purpose of the survey fill out. It was done in order to maximize the number of rescuers who could be employed in the process of knowledge acquisition and simultaneously limit the amount of time which the knowledge sources had to spend on the process of knowledge extraction phase.

We consulted an early version of the surveys with our domain expert (MSc. Eng. Piotr Golicz) and introduced suggested modifications. The final version of each survey contains information about a suggested solution which was directly followed by questions related to the described areas (example of a question from the survey see fig 3.2.1 - right).

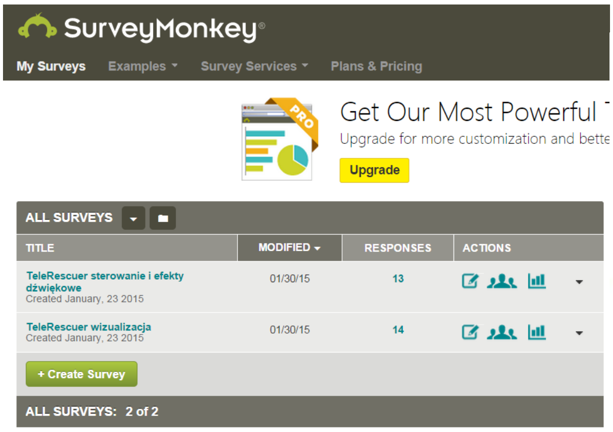


Fig. 3.2.1. Survey Monkey – tool for creation of survey (left); Slide taken from one of surveys that were prepared (right)

Polish language is native for all the rescuers, employed in the process of knowledge acquisition, therefore surveys were prepared in Polish language in order to facilitate communication and rule out possibilities of occurrence of incomprehension of presented content (as well as questions).
Surveys were created in SurveyMonkey (SM), which is a widely known, web based, system for knowledge acquisition (see fig. 3.2.1). SM allows for rapid application of advanced surveys with many various controls utilized in order to obtain various information from the end users.

T3.3. Development of a knowledge-based methodology of virtual immersion

During this task knowledge obtained in T3.2, combined with the review conducted in T3.1, was utilized. The decision was made to equip the robot with stereoscopic cameras, two monocular wide-angle cameras, an infrared camera and the 3D scanner.

Our main domain expert pointed out the difficulties with sound acquisition and tactile stimulation. Mining environment is noisy, in addition the operator mainly would hear the sound of the robot motors and mechanisms during its operation. As a result, the utilization of auditory stimulation would not increase the level of the operator immersion, potentially it can even make it worse because of disturbing sounds of the motors. Installation of microphones would also complicate the structure of the robot and make it more difficult to pass the process of ATEX certification. Therefore, the decision was made not to use this subsystem in the TeleRescuer project.

A similar decision was made in case of tactile stimulation, inclusion of force feedback at the level of the controller would not give meaningful information to the operator. Potentially utilization of 6 DOF movement platform could increase the immersion, however, for the cost of the operator station mobility, in addition according to some experts an application of the tactile stimulus could lead to acceleration of operator’s fatigue onset.

Based on the survey made in T3.2 concerning visualisation methods we decided to use 3D stereo visualisation techniques for the purpose of the robot’s surrounding presentation. In this survey, we asked the rescuers from CMRS whether the utilization of 3D techniques will support conduction of the rescue action. Most of the responders claimed that 3D techniques would fulfil this requirement (over 85%). After the review of techniques for 3D visualisation we selected solution based on 3D screens that utilized:

- NVIDIA 3D vision based active shutter glasses technology,
- anaglyph technology.

The user is able to decide which mode should be utilized by the TeleRescuer application. Huge advantage of an anaglyph-based solution is the price of glasses (fig 3.3.1 - left) which are very cheap (on average 50 pairs of anaglyph glasses can be purchased for the price of a single pair of Nvidia 3D glasses), it can work with any kind of display and 3D effect is clearly visible, the anaglyph-based glasses are also more reliable and shock-resistant than the active glasses. In addition, it is not necessary to apply the screen dedicated for 3D technology. Importantly this concept has one disadvantage. It is not possible to present properly all the colours of the streamed video, because of the coloured filters used in the glasses.

The second method is based on the Nvidia 3D Vision technology. This solution requires the display dedicated for this technology and the active glasses (shown on the right side of the figure 3.3.1). Screens working with the Nvidia 3D Vision are characterized by a high refresh rate, not less than 120Hz. This solution is much more expensive than the first one, but the 3D effect and quality of the view is significantly better.

Fig 3.3.1. Anaglyph and NVIDIA active shutter glasses (left), active shutter glasses in action (right).

We also checked whether preliminary version of the user interface based on various types of controls for data visualisation would allow for efficient control over the robot movements, twelve out of fourteen responders claimed that it would fulfil this task, two rescuers stated that they do not have an opinion in this area.

Among the devices for robot controlling, which were considered at the level of system design there were the following:

- Gamepads (fig. 3.3.2 A),
- Joysticks (fig. 3.3.2 B),
- Wheels (fig. 3.3.2 C),
- Professional robot controller (fig. 3.3.2 D),
- Plane controllers (fig. 3.3.2 E),
- RC like radio transmitter (fig. 3.3.2 F).

Fig. 3.3.2. Type of controllers which were presented to the rescuers during the survey action.

During the knowledge acquisition phase we asked the professional mining rescuers from CRMS about the type of controllers which they were familiar with. The conducted survey pointed out that the most popularity gained gamepads and joysticks, it is related with the availability of these controllers in home entertainment systems, more than 50% of responders claimed that they often used such devices. On the other hand, rescuers are not familiar with professional robot controllers (D), plane controllers and RC model controllers (E). However, utilization of plane controllers should be similar to utilization of a car's steering wheel and most of rescuers are familiar with this device. Our opinion seems to be shared by rescuers, when we asked specifically whether control system based on plane controllers would allow for efficient controlling of the robot's movement. Almost 70% of responders answered 'definitely yes' or 'yes' and only 15 % of rescuers stated that such controllers would not be a good fit for this task. The same question was asked about a gamepad utilization, 65% or rescuers stated 'yes' or 'definitely yes', however almost 40 % stated that it would not be an appropriate solution. Similar results were obtained in the direct comparison between devices.

As a result of the conducted survey we decided that the system would be modular in the area of controllers. Therefore, both the plane controllers and gamepads are utilized.

T3.4. Prototyping software and hardware of the human-machine interface

The TeleRescuer Human-Machine interface consists of two parts:

- hardware that is exploited for robot movements controlling as well as delivers the platform for visualisation of the data obtained from the robot,
- software components that are responsible for presentation of the data on provided hardware components.

The most important components of the user interface that were implemented during TeleRescuer project are as follows:

- Stereoscopic camera visualisation with Head-up display (HUD) – the component that displays stereoscopic representation of the data acquired from the cameras installed on the robot. It has two separated modes for anaglyph and active shutter glasses. The stereoscopic part is based on a custom player based on the DirectX for the NVidia 3D support and VLC component for the anaglyph-based stereovision.
  HUD control is located directly on the top of the window with stereoscopic environment representation. It gives an additional information about the position of the robot in 3D space. The component introduces an innovative functionality of the augmented reality into the operator station, which allows the virtual teleportation of the operator into the scene of operation of the mobile robot (fig. 3.4.1).

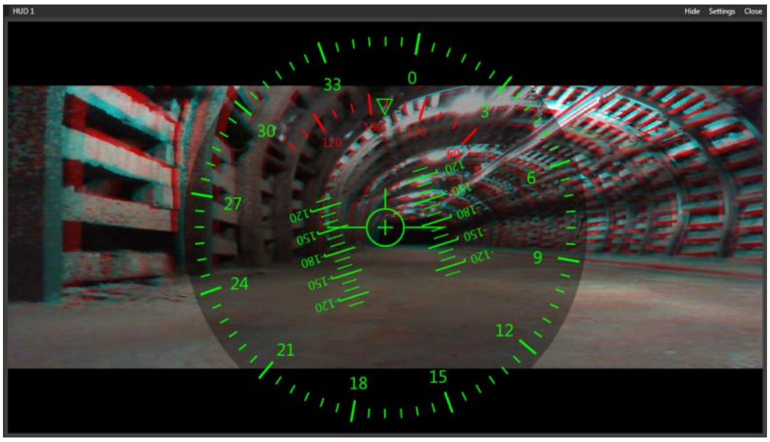


Fig 3.4.1 Stereoscopic cameras and HUD

- 2D / Infrared camera – a control which is responsible for displaying the data obtained from wide-angled cameras and infra-red cameras installed on the robot. It is based on libVLC library (fig. 3.4.2).

Fig 3.4.2 Regular camera view (left) and infra-red camera view (right)

- A point cloud viewer – a specially designed control for visualisation of point clouds obtained from the 3D laser scanner installed on the robot. It accepts point clouds in ASCII format, as well as binary one (for the reduction of the amount of transmitted data). In order to obtain better orientation in the robot surrounding, the operator can freely navigate within obtained 3D representation of the environment (rotate and move the camera). In addition, there is a possibility to select the colour of presented points and the colour of the background on which points are presented. In addition, for the performance purposes, the whole component is based internally on a sparse partitioning data structure called k-d trees that gives high performance even if millions of data points must be processed (fig. 3.4.3).

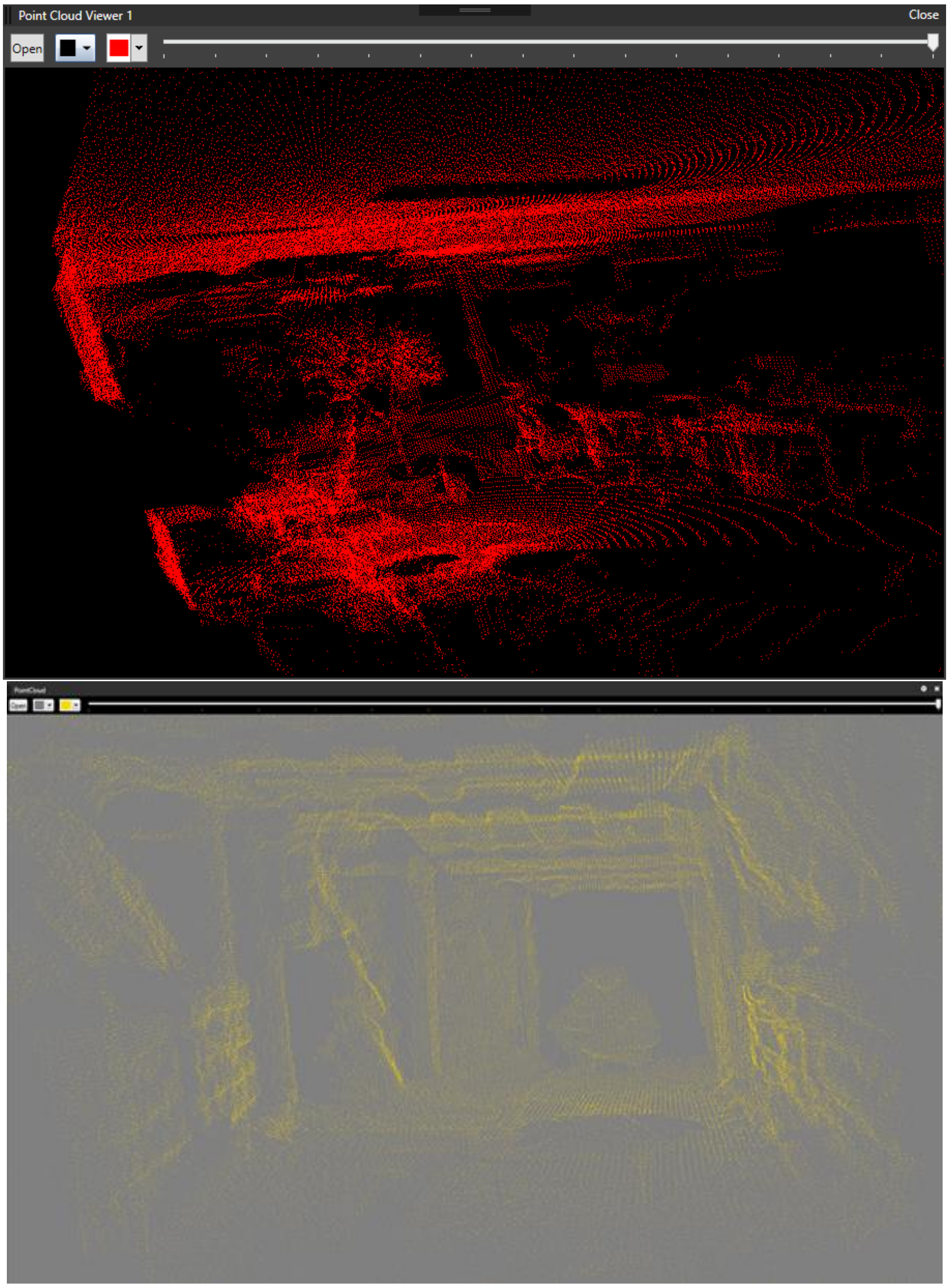


Fig 3.4.3. Point cloud viewer (various colours)

- Gauge – a control that is utilized in order to present readouts obtained from sensors such as external temperature, methane, CO, CO_2 etc. The range of the scale as well as ranges of colour areas (green, orange red) can be defined independently for each sensor. In addition, the latest value, obtained from the sensor is displayed in textual form below the sensor name (fig. 3.4.4).

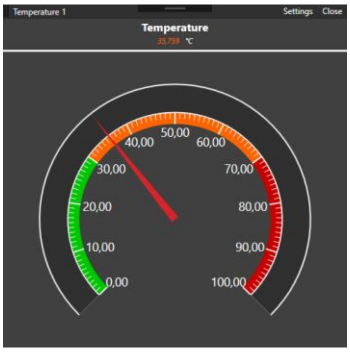


Fig. 3.4.4. Gauge

An analysis conducted in the area of the operator station has led to the conclusion that the operator station should be mobile. Therefore, the decision was made to create a special case that will be able to carry all the components necessary to conduct the action with the Tele Rescuer robot.

A mobile operator station (MOS) was designed in a way that it is self-contained, it has all the elements necessary to communicate with the robot, to control the robot movements and to visualise data obtained from the robot:

- monitor,
- 3D glasses (active and passive),
- infra-red emitter (required by active glasses),
- plane controller,
- game pad,
- keyboard,
- mouse,
- workstation,
- communication devices.

The purpose was to obtain the operator station that was easy to use and required minimum number of actions to become operational. The operator should be able to start controlling the robot movements after execution of the following steps:

- open mobile operator station case,
- plug it into the power source and communication medium,
- turn on the workstation,
- take out the controllers and 3D glasses.

A custom-made case was designed (fig. 3.4.5, fig. 3.4.6). On the outside the case is covered by a resistant metal shield. Inside, it is enforced with plywood. Such an approach allowed to obtain high stiffness and significant reduction of the container weight.

The case is internally equipped with the plane controller that is located behind a closed door, and is installed on the sliding gibs, therefore the operator could slide it out from the case easily. The controller locks automatically in the pulled-out position. Next to the controller the workstation elements are located. Components of the workstation were distributed evenly on the left and right side of the box in order to balance its centre of gravity. On the left side of the box, a space is reserved for the installation of communication devices (optical-Ethernet converter etc.). On the right side the components of the workstation are located. The case internals are ventilated by two fans to which anti-dust protectors are attached. The space with the controller and the workstation is covered by a bulkhead to which the gamepad, 3D glasses, mouse and keyboards are fastened. To the internal side of the case's top cover a monitor is attached. As a result, the top cover has significant weight, in order to protect the operator's hands and fingers against uncontrolled closures of the case cover (e.g. in case when one is writing on the keyboard) air springs were installed that open the top cover automatically and keep it open all the time.

Within the station the ROG SWIFT PG278Q monitor was installed. It delivers high resolution (2560x1440 pixels) therefore all UI components can be aligned without issues on the screen surface. Special handles were installed on the left and right side of the case in order to facilitate the process of the case transportation.

Fig. 3.4.5. Mobile operator station with a carrying frame

Fig. 3.4.6. Mobile operator station with the TeleRescuer application running.

T3.5. Virtual teleportation technology integration

Within this task an integration of the virtual teleportation software and hardware components with the robot hardware and software was done.

Communication protocols between the robot and the operator station were implemented and integrated with the virtual teleportation technology hardware. The protocol is based on the telegrams that have specific word structure presented in the tab. 3.5.1.

Tab. 3.5.1. Telegram data scheme

1B	4B	4B	4B	<Length >	1B	1B
Start	TimeStampGuid	CW	Length	Data	CRC	End
"stx"						"etx"

The telegram contains a few fields, most of them have specified constant size. Some of them are equal to a constant value. Below a description of each field is presented:

- Start – Start byte "stx" (02 Hex)
- TimeStampGuid - Individual id of every message based on the current time (format: hh,mm,ss,msmsms). It is used for the purpose of message tagging and each message has different TimeStampGuide value inside
- CW (Control Word) – The first part of the word (bits from 23 to 0) contains a code of the command. The remaining part of the word (bits from 31 to 24) has information about flags
- Length – Length of the Data field in bytes
- Data – Data with variable length
- CRC – Cyclic redundancy check
- End – End Byte "etx" (03 Hex)

The operator station can communicate with the server over two different approaches: "Command/Answer" and "Command/Auto answer". The Command/Answer approach (fig. 3.5.1 left) is basically used to set parameters on the server. When the server receives and correctly decodes the telegram, the server will send back the answer to the client. In most of the cases, an answer is only information for the client that the telegram was received properly. Some of the commands use the Command/Answer approach to get some parameters or values from the server on demand. The second solution (fig. 3.5.1 right) is used only for data received from the server. When the server receives a command from the operator station it starts to send back auto answer telegrams to the client. Answers are sent periodically, and frequency of answers is set in the first command sent from the client to the server.

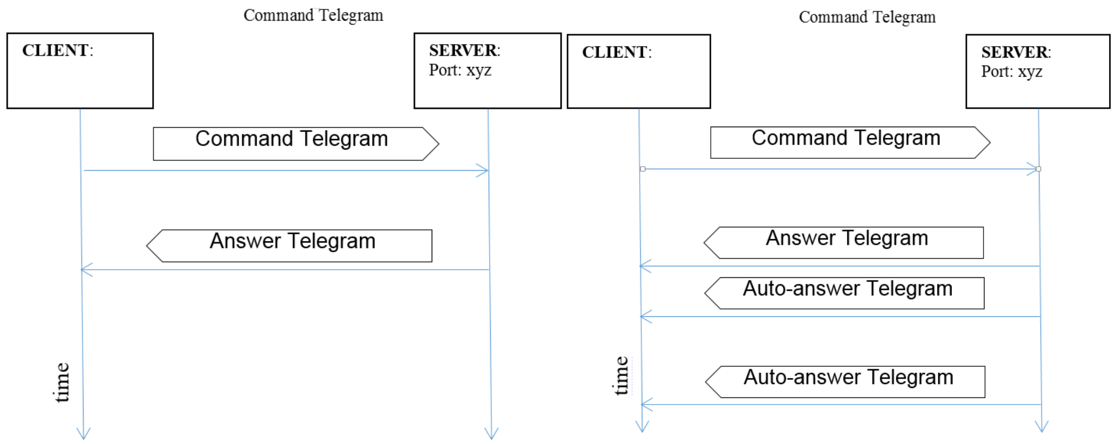


Fig. 3.5.1. The communication between Client and Server: the Command/Answer approach

The visualisation system is receiving data directly from the robot cameras. A diagram of the internal structure of a stereoscopic stream visualisation component as well as 2D visualization controls is presented in fig 3.5.2.

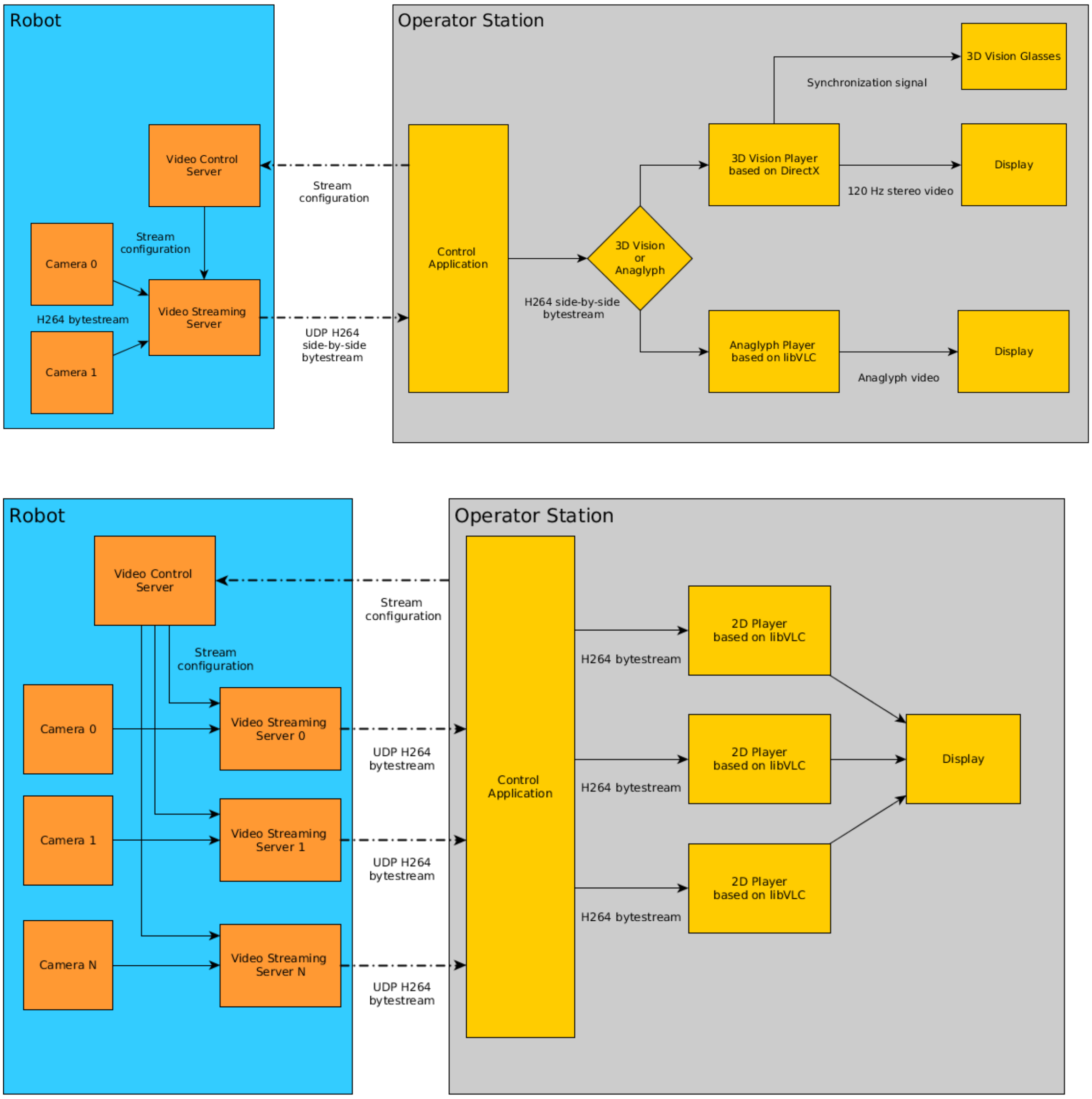


Fig. 3.5.2. Structure of 3D vision controls and connectivity (top); structure of 2D video controls and connectivity (bottom)

In addition, in this task the controllers were integrated with the robot operation modes.

T3.6. Prototyping 2D/3D visual hardware/software system for training simulator

Software utilized in the simulation operator station (SOS) and MOS is based on the same TeleRescuer application. Modifications were introduced into the application in order to be able to recognize visual signals delivered from the simulator. From the point of view of the software there is no difference in communication between the physical robot and the simulator. Therefore, SOS and MOS can be used interchangeably either for controlling the robot or controlling the simulator. There is a possibility to have SOS station set up constantly in one of mine buildings, on daily basis it can be used in order to train rescuers based on simulation software. However, in case of such a need it can be linked with the physical robot and allow controlling its movements remotely. Workstation components in SOS are similar to MOS when it comes to computational power. MOS and SOS use the same controllers.

For the purpose of visualisation 32 inch curved display was applied (ROG PG328Q fig 3.6.1). It is bigger and heavier than the monitor installed in MOS however it allows to obtain even higher level of immersion and comfort during long hours of training sessions.

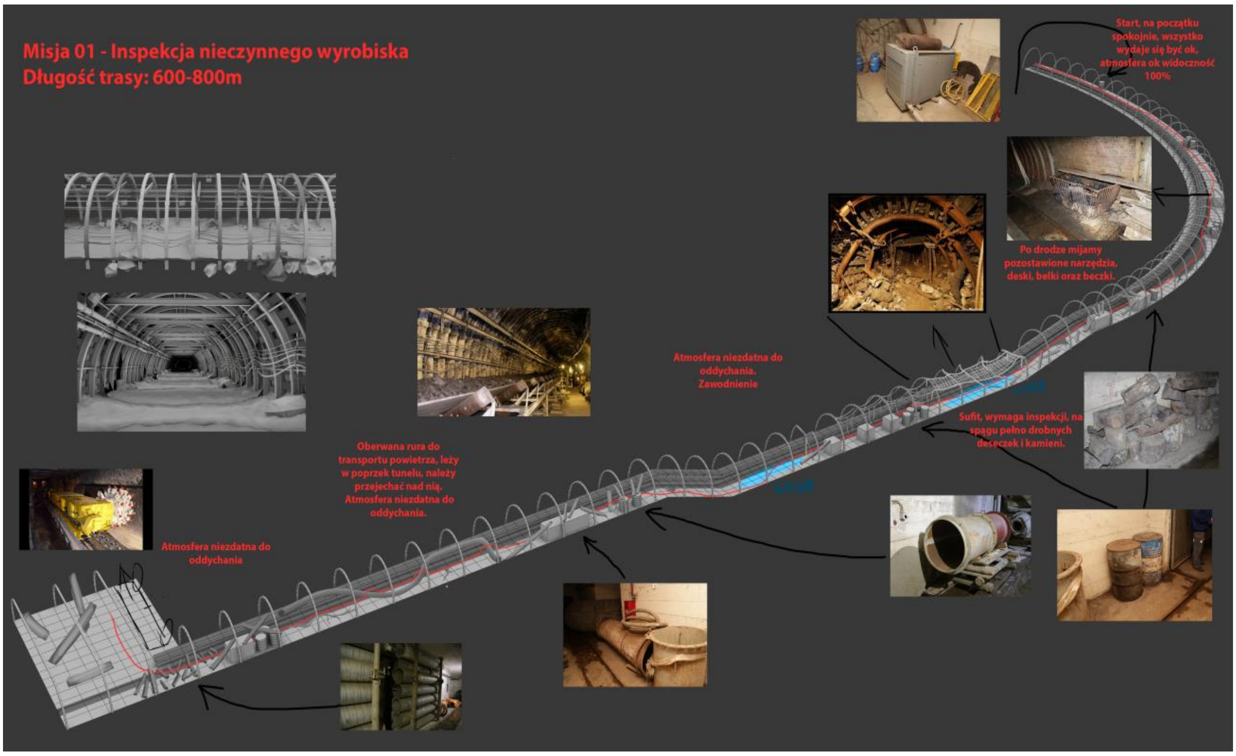
Fig 3.6.1. ASUS ROG PG328Q

T3.7. Development of methods for realistic simulations

Within this task, together with the experts from the Central Mining Rescue Station, the following scenarios of various types of rescue actions were defined:

- Scenario 1: Inspection of an inactive mining site
  The purpose of this scenario is to measure the state of the atmosphere in various locations of the inactive mining site as well as inspection of the wall supporters (Fig. 3.7.1 upper)
- Scenario 2: Inspection of a mining site after conflagration:
  The purpose of this scenario is to measure the state of the atmosphere in various locations of the mining site, as the check whether there are still active sources of conflagration (fig 3.7.1 bottom)
- Scenario 3: Rescue of miners staying in provisional shelter:
  The purpose of this scenario is to locate rescuers that are staying in provisional shelter after a catastrophe. Miners cannot evacuate because of concentration of poisonous gases in the corridors (fig. 3.7.2 upper)
- Scenario 4: Rescue of the miner after corridor collapse
  The purpose of this scenario is to locate the miner as well as to measure concentration of gases in the atmosphere (fig. 3.7.2 bottom)

In addition, the deliverable *D3.2 A report on the simulations of the operations of rescuers in a hazardous area of the coal mine* discusses methods for realistic simulations for the purpose of the training simulator implementation.



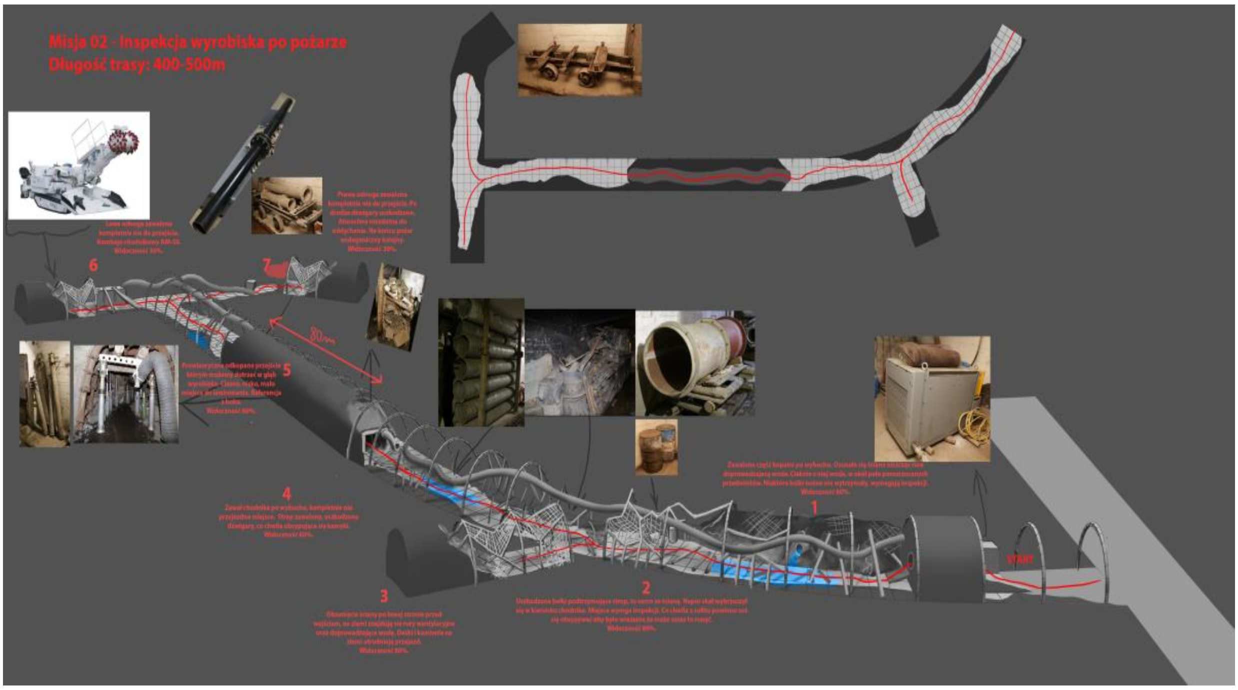
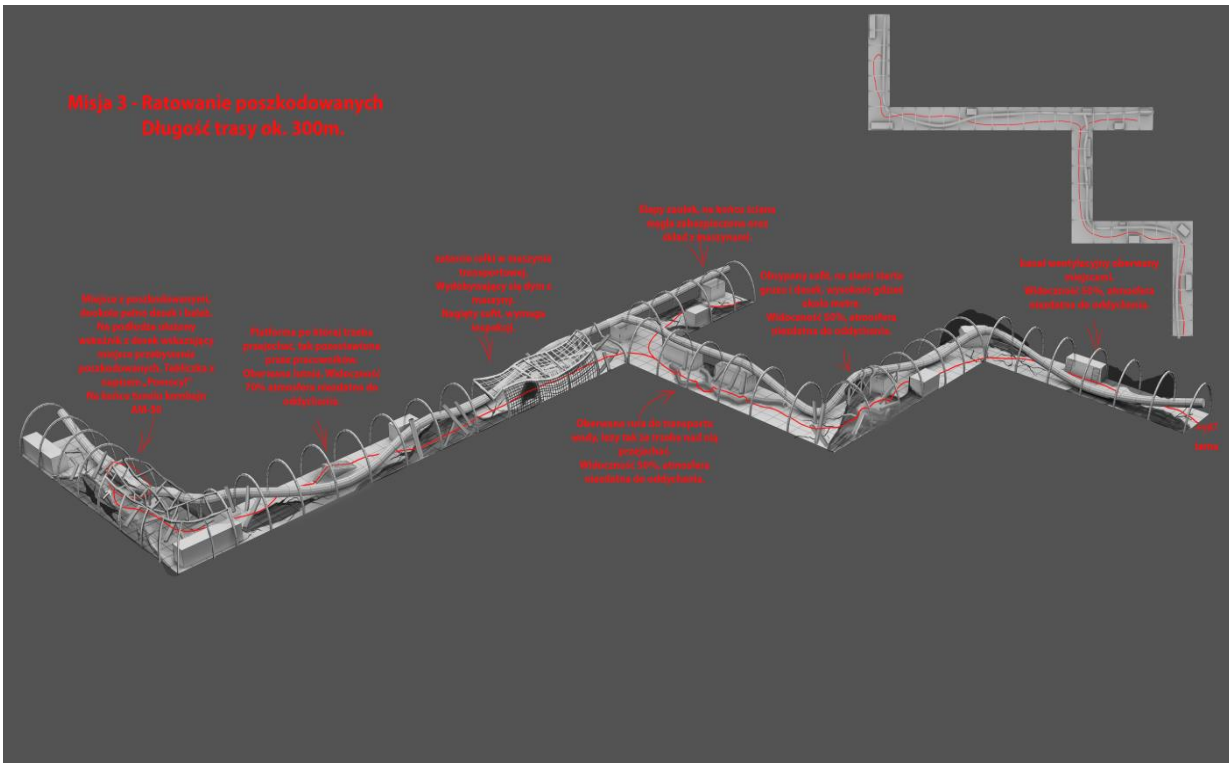


Fig. 3.7.1. Scenario 1 (upper), scenario 2 (bottom)



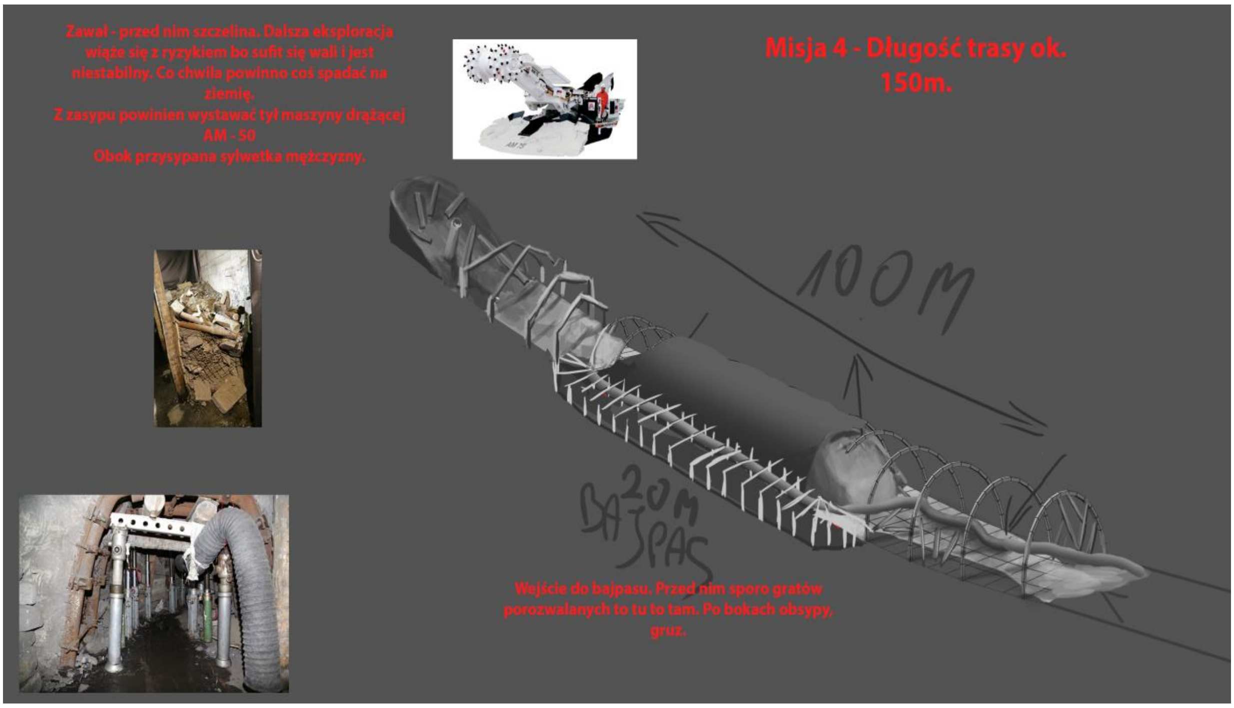


Fig. 3.7.2. Scenario 3 (upper), scenario 4 (bottom)

T3.8. Prototyping human-to-machine interface for training simulator

Special simulator operator station (SOS) designated mainly for simulation purposes was designed and developed (fig. 3.8.1, fig. 3.8.2).

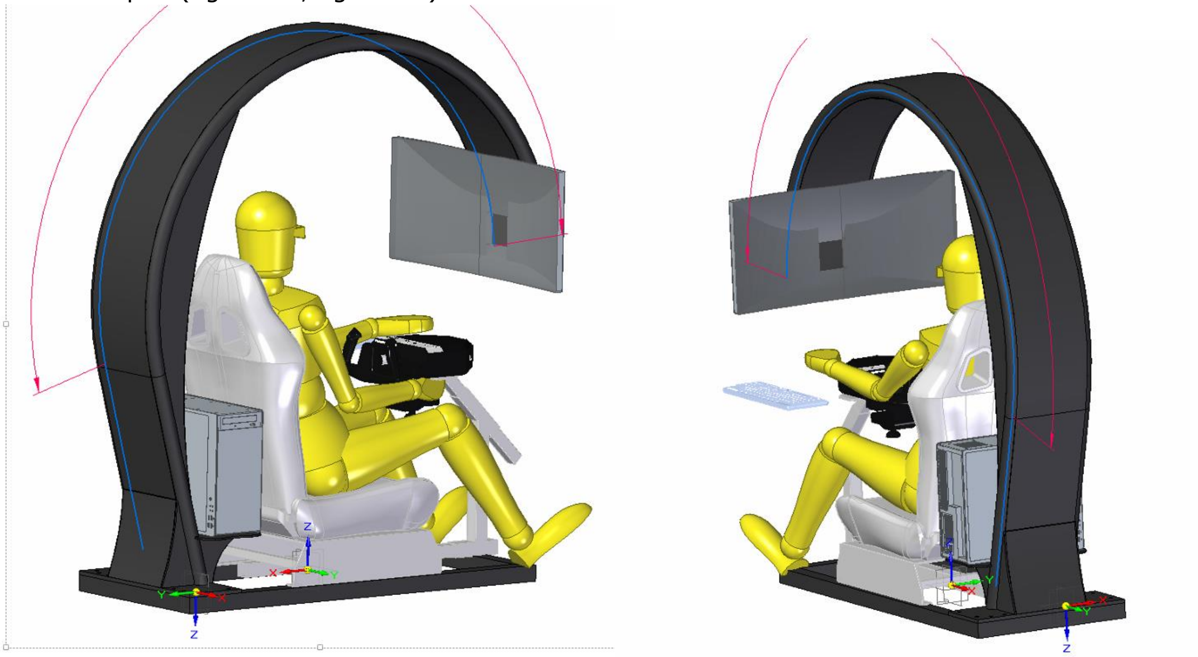


Fig. 3.8.1. Design of SOS

Fig. 3.8.2. Physical SOS with the robot and MOS

The equipment utilized in the simulator operator station uses the same elements as MOS at the controlling and visualisation level (gamepad, plane controller, workstation, communication elements etc.).

Utilization of the same controlling components is justified by the fact that the operator should learn how to control the real robot based on the training in a virtual environment. Therefore, the same components, as well as the same mapping of the controller movements to the repertoire of the robot actions was utilized.

The main difference between SOS and MOS consists in the comfort of the operator and in the station mobility. In order to be able to conduct simulated sessions for prolonged amount of time, SOS is equipped with a comfortable chair to which controlling elements are mounted.
SOS is modular, it contains the following parts:

- comfortable armchair connected with the controllers,
- monitor connected with the stand,
- workstation.

Such partition of the station elements significantly facilitates the transportation process.

T3.9. Training simulator software development, system integration and extensive testing

The training simulator basing on V-REP (Virtual Robot Experimental Platform) was developed that allows for the training of the operator. The engine of the simulator was implemented in LUA language. The simulator allows to simulate the robot operations such as the robot movement (arms / tracks, towers), obtain data from the virtual cameras and transfer it to the SOS etc.

Physical characteristics of the robot such as its weight and behaviour of the tracks were taken into account. A TeleRescuer robot model was created in simulation environment (fig. 3.9.1).

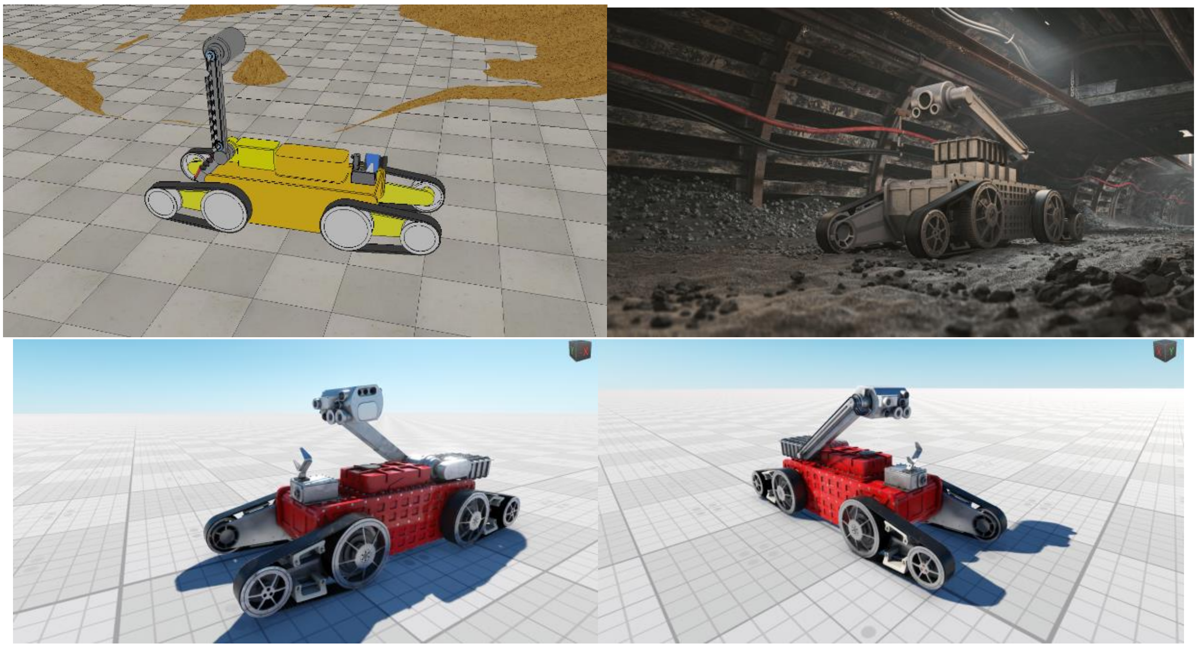


Fig. 3.9.1. V-REP simulator with the robot (top left), models of the robot in virtual environment (bottom) and in the mine (top right)

The communication protocols created in T3.6 were implemented, they were in accordance with the protocols utilized for the robot operation. Therefore, the simulation operator station can be connected with the robot or the simulator interchangeably.
SOS was integrated with the simulator through the Ethernet network and series of test were performed which allowed for validation of SOS as well as the simulator.
Internal tests of MOS and SOS were performed such as movements of the robot arms and correctness of the controllers' operation; movements of the tower with cameras; transfer of the visual data; sensor readouts.
The testing phase allowed to rule out errors that were not caught at the level of MOS, SOS and the simulator development and validated that the product is working correctly.

2.2.4 Field test of the system and its components

Within a workpackage **WP4 Field test of the system and its components** the following tasks were realised:

- Setting up the detailed plan of tests
- Carrying out the tests
- Reporting the tests;

T4.1. Setting up the detailed plan of tests

Regarding to field tests of the system and its components two types of tests were planned: laboratory tests and tests in real conditions (in a coal mine or coal mines). Test environments had to constitute real environments for the operation of the system, including the operation of real machinery such as working mining equipment, but without the hazard of explosion or fire. The plan of tests included:

- The analysis of the performance of the UV;

- The analysis of the data transmission system’s performance;
- The analysis of the teleportation/virtual immersion ergonomics and feedback issues;
- The correct operations of UV in real operating conditions and the assumed kind and size of obstacles;
- The correct operation of auxiliary equipment for arranging communication and the measuring content of air across the tunnel cross-sections;
- The achievement of the assumed parameters of broadband communication in real working conditions;
- The reliable collection of accurate values of the signals measured by the sensors installed on the UV;
- The faultless operation of the video and IR imaging system, including the fusion of images;
- The faultless operation of UV in the remote-control mode;
- The reliable operation of the UV in autonomous operation mode;
- The confirmation of the effect of the virtual immersion of the rescuer into the hazardous area of operation.

All system elements of the UV were subjected for testing (fig. 4.1.1).

Fig. 4.1.1. UV with all subsystems installed, used for final tests

T4.2. Carrying out the tests

Initial verification of subsystems was realized in laboratory conditions as well as in real conditions, including: tests of the system for map building (in the Queen Luiza Coal Mine), tests of operation with the use of batteries (in the laboratory of SUT and STR and in the Queen Luiza Coal Mine), tests of the sensory system (the Coal Mine San Nicolas in Area Sueros), tests of cameras (in the laboratories of UC3M).

First tests of wireless communication system as well as sensory system were realised in the Coal Mine San Nicolas in Area Sueros, located in Asturias, Spain. The coal mine is an unknown environment regarding the communication system. Thus, real measurements need to be done in such an environment to get to know the electromagnetic waves propagation to properly design the wireless communication system. Fig. 4.1.2 shows two scenes where these measurements were being taken.

Fig. 4.1.2. Tests of communication and sensory systems in a real coal mine

The measurements were made with a prototype of the wireless communication system by using the developed hardware. Two devices were configured in an ad-hoc network. Propagation measurements were carried out in two different environments as shown in Table 4.1.1.

Table 4.1.1. Conditions in the coal mine

Parameter	Normal Conditions (NC)	Bad Conditions (BC)
Air velocity (m/s)	0	2.2
CH_4 (% vol)	0	0.4
CO (ppm)	0	15
CO_2 (% vol)	0	0.15
Temperature (ºC)	17	23
Humidity (%)	60	100

Fig. 4.1.3a depicts the received signal strength with respect to the distance. As expected, the curve follows logarithmic models. Measurements in NC scenario with Line of Sight (LoS) show the best conditions to establish a wireless communication in the 2.4GHz band. However, when both transceivers are close to the right side of the gallery, it presents a loss of 10dB approximately at a distance of 30m. Besides, Non-LoS (NLoS) is studied by interposing a battery locomotive between both the transceivers, and around 10dB is lost in signal strength. Environmental conditions were also studied, and the propagation is influenced when it is performed in a BC scenario. Around 5dB are lost at a distance of 80m, when the performance is compared in NC and BS scenarios for LoS. NLoS in BC scenario was performed in a corner. It creates additional 5dB in loss approximately at a distance of 20m. The achievable data rate between the two devices is evaluated in Fig. 4.1.3b. Note that above 5Mbps is obtained at a distance of 80m in normal conditions and LoS. It is more than enough for sending a video stream from the robot to the operator station. However, when both transceivers are close to the right side of the gallery, such proximity inserts losses in the system which means a significant reduction of data rate. Again, note that environmental conditions influence the system performance. The realised tests confirmed usability of the developed subsystem for communication.

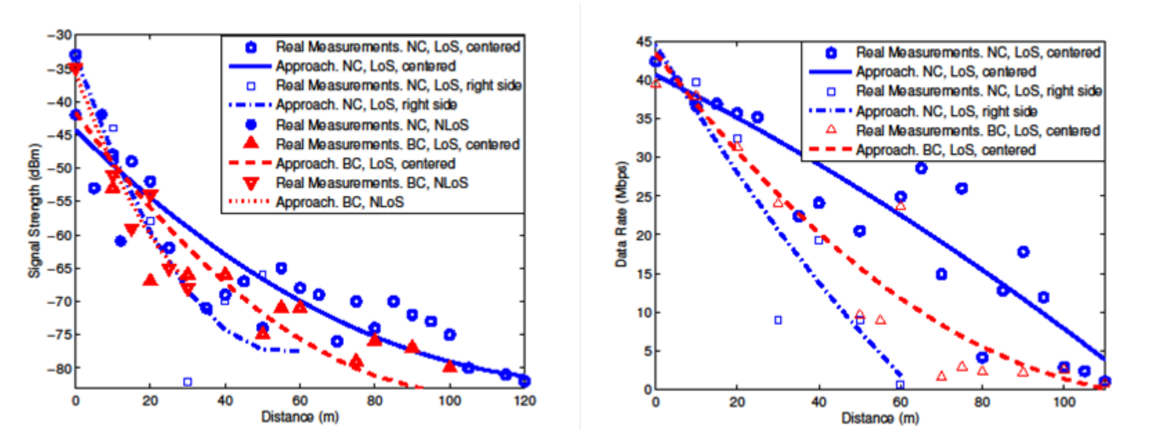


Fig. 4.1.3. WiFi received signal strength (a) and WiFi data rate (b) measurements in a real coal mine, respectively.

Tests of the system for map building based on a 3D laser range finder (LRF) were also realised in real conditions, in the Coal Mine Queen Luisa in Poland (fig. 4.1.4).

Fig. 4.1.4. Place of test in Coal Mine Queen Luisa

Results of these tests are described in section **5.3.2 Research into the UV, T2.4. Development of methodologies for building maps** in this report. During the tests there were acquired many thousand-point clouds in different distances in the tunnel. The prototype of 3D LRF worked well during the whole measuring process. Initially, the only one small problem was with the position sensor, which seldom sent bad data of inclination. The problem was diagnosed later and has been already eliminated. Summarising these tests, it is necessary to notice that the system works as required. Exemplary results of the scanning process are presented in fig. 4.1.5 and 4.1.6.

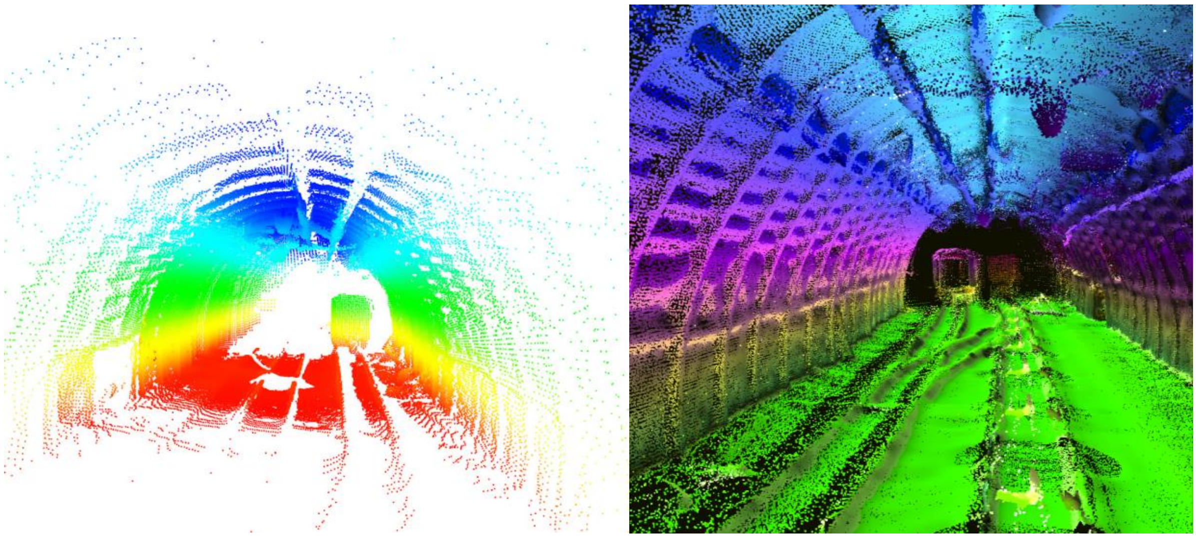


Fig. 4.1.5. The coal mine Queen Luisa place of tests and captured point cloud before and after image processing

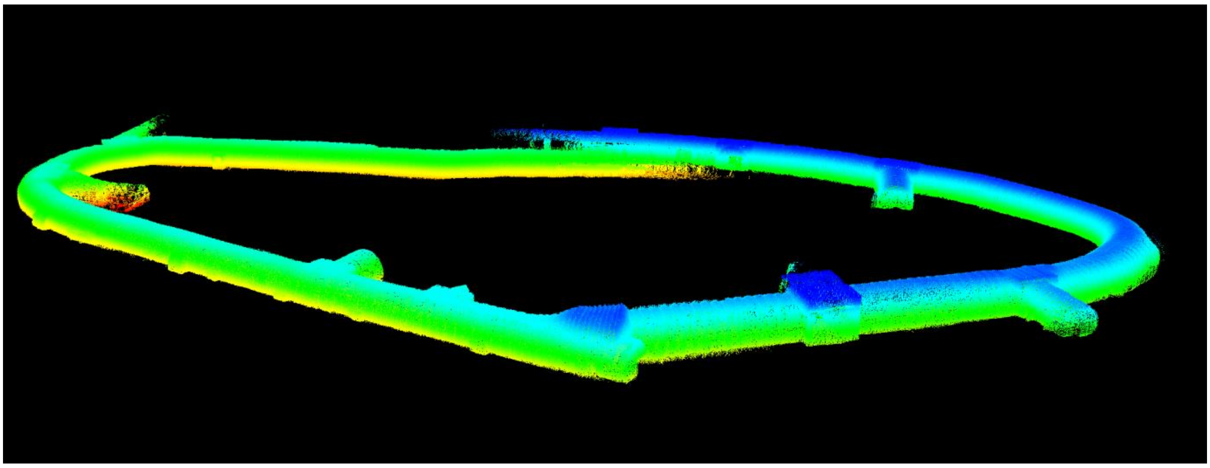


Fig. 4.1.6. Map of scanned tunnels in a coal mine – the final result of the tests

Final tests of the whole system were carried out in the practice mining excavation of the CSRG Central Mining Rescue Station in Bytom (fig. 4.1.7).

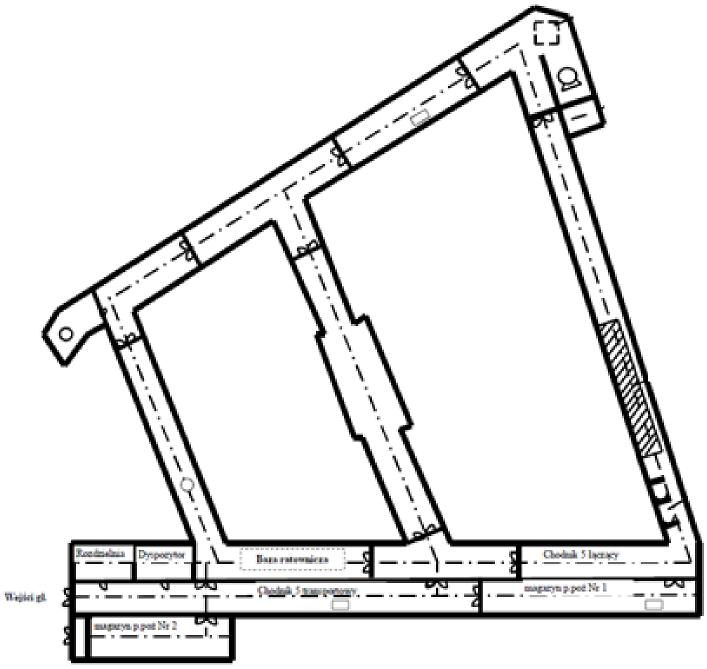


Fig. 4.1.7. Draft of the practice mining excavation of the CSRG Bytom.

During final tests a task was to check capabilities and suitability of the system (especially UV) for applications in underground mining, in the space in which an accident or disaster occurred. The functionality of the device has been verified in several basic ranges. Main conclusions from tests are as follows:

- The mobility of the robot is limited primarily by the mass of the robot itself and not enough contact of the tracks with the ground (resulting from the way to protect the crawlers from sliding off the driving wheels and the type of caterpillars used). The consequence of the above is the difficulty in accurately positioning the robot. It has the tendency of losing contact with the ground and slipping. In addition, the problem is hampered by low ground clearance, which can be increased, but at the expense of lowering the driving parameters. It seems that changing caterpillar tracks for more customized ones should largely solve this problem.
- The maneuverability of the robot is good, but still insufficient to use it in the underground mines. The control system should be supplemented with algorithms that would help bypassing obstacles on the route. The tests confirmed the possibility to avoid typical obstacles and overcome the hills (fig. 4.1.8, fig. 4.1.9).

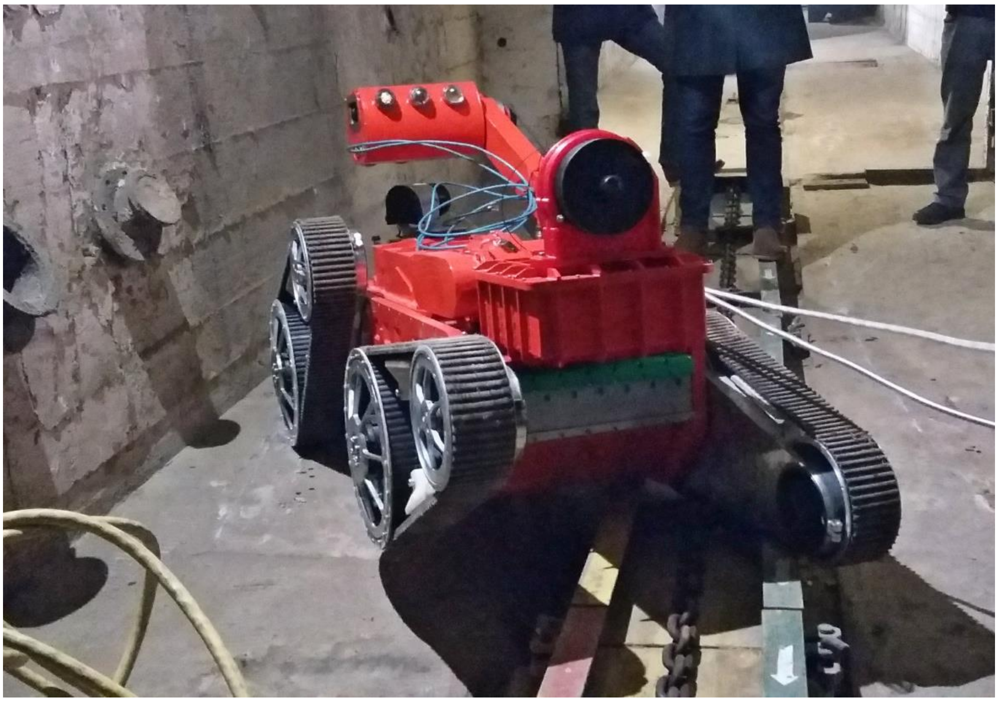


Fig. 4.1.8. UV passing through the conveyor

Fig. 4.1.9. UV Passing a concrete block

- Currently, the robot control requires constant observation by the operator. Better visibility of the environment around the UV is recommended.
- The mechanical strength of the structure is generally satisfactory. The biggest reservations concern the drive auxiliary wheels, which consequently caused that the caterpillar track slipped off the rim in some cases.
- The resistance to environmental conditions has not been verified during the tests. However, during the general inspection, it could be seen that the covers of the main body of the robot were secured with O-rings. This should protect the structure sufficiently enough against contamination and water. It should be borne in mind that the device will work in a highly dusty environment and will overcome water-filled cavities.
- The efficiency of the built-in energy source was not the object of research, because the tested unit was not equipped with it. All the tests were carried out using an external power supply provided with an electric wire. The tests of the operation with the use of batteries were realized earlier (fig. 4.1.10) in the Coal Mine Queen Luisa. The reason of operation with the use of external power supply during final tests was a duration of the tests. The tests lasted more than 8 hours therefore operation with the use of the batteries was not possible (respecting to 4 hours necessary to charge batteries safely).

Fig. 4.1.10. The UV during initial tests with the use of batteries

- The robot has slightly exceeded the assumed dimensions. This prevented passing through the Ø 800 mm hole. At this point, the assumptions of the CMRS should be verified. Whether the assumed Ø800 is impassable or not. There is also a good chance of limiting the size of the robot in the prototype version.
- The used system cameras allow to present a view around the UV. However, it requires a thorough refinement. In particular, the system must be protected against possible damage (independent power and communication circuits), because its failure will make it impossible to control the robot. Thus, the rescue operation will be impossible. The introduction of redundant vision and sensory systems should be considered. These systems will guarantee constant access to the parameters of the monitored environment (robot's environment).

T4.3. Reporting the tests

After the tests a comprehensive report (**D4.1 A report on tests of the system and its components)** was produced containing all the results acquired, and the opinions of the rescuers and miners who participated in the tests, etc. The report includes a compilation of the major observations and conclusions in order to provide a set of recommendations to improve the system. The report is presented in Appendix 2.

2.3 CONCLUSIONS

During the last two decades, there has been a lack of clear ways to eliminate the risk of injury or death faced by rescuers in coal mines in case of major accident hazards, like rock bursts, gas explosions and fire, etc. To increase the safety of rescuers and improve the efficiency of the operation of human rescuers, research within TeleRescuer project was conducted into an unmanned system that included a highly advanced interface equipped with a wireless broadband communication system, allowing the virtual teleportation of the rescuer to the hazardous area of operation, a very realistic 3D simulator, and a special UV carrying sensory systems, cameras and actuators, which were capable of moving within the area of a coal mine affected by the catastrophic event.

The general objectives of the proposed research work were as follows:

- Preparing a detailed specification of the requirements connected with rescuers' operations and inspections of machinery and equipment in coal mines and the operating conditions of the UV, etc.;
- Designing and building an optimised mechanical structure of the mechatronic carrier of the UV for locomotion in environments with a variety of obstacles;
- Designing and building a broadband communication system with a range of more than 500 m in a closed subterranean space from the dam up to a mining disaster site;
- Designing and building an effective control system for the UV;
- Implementing a sensory system for collecting data and signals from the area affected by the catastrophic failure;
- Designing and building a sensory system and methods for building maps of an unknown environment and for autonomous navigation in a known environment;
- Implementing a knowledge-based methodology and a system for the virtual immersion (teleportation) of the rescuer in a hazardous and inaccessible subterranean space affected by a catastrophic event;
- Developing methods for the realistic simulation of the operations of a rescuer virtually immersed in an environment to be efficiently implemented by a very realistic simulator;
- Achieving the reliable operation of at least one ATEX-ready UV in the natural environment very similar to a working coal mine.

The final result of the project is a test version of the system, including the working realisation of the mobile robot. All the important subsystems of the robot (including the robotic carrier, the communication system, the sensory system including cameras, the operator station, the 3D map building system) were tested and validated in the relevant environment. The majority of parameters defined at the WP1 has been met. Furthermore, the system after integration phase was extensively tested. The most important properties concerning mobility, controllability, communication capabilities, and the user-friendliness of the interface have been achieved. All the subsystems are able to undergo the ATEX certification process required for safe operation in a coal mine. The laser scanner subsystem could satisfy ATEX M2 requirements, while other subsystems (robotized carrier, sensory systems, communication systems, control system, cameras and so on) could satisfy ATEX M1 requirements. However, this certificate could not be applied for since it is reserved to the manufacturer of the final product. Additionally, advantages of the advanced human-machine interface equipped with stereovision functionality have been confirmed. This solution allows 'virtual immersion' of the operator into the scene of operation of the mobile robot. Finally, a simulator of the complete system was presented.

The tests allowed to detect some weak points of the developed system. Lessons learned from the project can help in the further evolution of the developed solution to develop a system with commercial value. In particular, there should be a simplification of the mobile platform solution that is the basis for sensory and vision systems. The result of these activities should also be a significant reduction in the weight of the mobile robot and keeping dimensions so that it can get through the lock in a typical fire dam. Furthermore, reliability of work of several assemblies of the system should be increased.

The consortium is going to seek the right source of financing the design and development of the second generation of the system for robotized inspection and diagnostics that could be implemented in the rescue services such as the Central Mining Rescue Station. The necessity of disposing of such equipment has been dramatically proven by a very last accident in a coal mine in Poland where in result of a very strong rockfall several miners have been trapped underground and some of them unfortunately lost their lives. If the Central Mining Rescue Station had such a system for inspecting roadways affected by a catastrophic event, then it likely would have been possible to locate the miners within the affected area and maybe to save lives of some of them.

2.4 EXPLOITATION AND IMPACT OF THE RESEARCH RESULTS

2.4.1. Actual applications

Nowadays, human rescuers must inspect the subterranean areas of a coal mine that have been closed off due to a catastrophic event that has occurred within the area, such as an explosion of methane or coal dust, a release of carbon dioxide or fire. The activity of rescuers is extremely dangerous, and has resulted in multiple deaths. Mine rescuers take a huge risk and must enter extremely dangerous environments by narrow passages with a diameter as small as 80 cm, to check the condition of the air and gain an insight into the overall situation. Human rescuers are allowed to enter the restricted area only if several values of critical variables drop below limit values, including methane content and temperature. Such missions are very dangerous.

Especially dangerous factors in coal mines include the risks of methane, fire (in particular - endogenous fires) and rockbursts or rockfall. The most important hazards are not visible to the naked eye, and are difficult to detect and deal with. During a catastrophic event, the concentration of toxic gases (methane, carbon dioxide and carbon monoxide) increases. Those roadways in which concentrations exceed the permitted values must be sometimes closed with the use of a dam or sealing system to control the situation safely. Unfortunately, the downtime involved in this exposes the mine to huge financial losses. Important equipment for coal mining remains trapped in the roadway behind the explosion-proof dams. After some time, in occasions lasting several months, the hazard is extinguished, which can be decided based on the concentrations of gases collected directly from behind the dams. These measurements are not carried out in the centre of the closed space due to the high risk involved in entering it. Such a measurement method has significant drawbacks, and can be unreliable (e.g., a fire might have extinguished itself much earlier on, while the results of measurements taken directly behind the dam will not indicate this fact). Unfortunately, due to the high risk to life, the rescuers cannot monitor the hazard accurately since they are not allowed to penetrate the hazardous area in-depth.

The accomplishment of the project required combining knowledge belonging to different domains of science and technology. In particular, several problems had to be solved that have not been solved until now, neither by the research community nor by industry. Examples are the absence of an effective wireless simultaneous broadband communication between the UV operating in a subterranean hazardous area and the operator (rescuer) staying in a safe place, or a very effective method for the virtual teleportation of the rescuer into the operation theatre, giving him the opportunity to personally participate in the action.

The result of the project is a methodology for the virtual teleportation (immersion) of the rescuer in a hazardous and inaccessible subterranean space affected by a catastrophic event, the test arrangement consisting of a UV capable of operating in an explosive environment, a high capacity modular and self-organizing wireless communication system and software allowing this virtual teleportation supported by a very realistic simulator. An application of the UV for inspecting closed spaces in a coal mine can revolutionise the operation of mining rescuers, and thus will allow:

- Eliminating hazards for rescuers inspecting the closed space of a coal mine;
- Reducing inspection costs and production losses caused by the closure of areas of catastrophic events;
- Carrying out inspections of the affected spaces significantly earlier when compared with inspections performed by human rescuers (because inspections will be conducted at higher temperatures and in hazardous atmospheres, and the ventilation of the space will be unnecessary, etc.);
- Producing and transmitting maps of spaces affected by catastrophes;
- Carrying out inspections more frequently (especially of the critical spaces of the coal mine);
- Decreasing risk of subsequent catastrophes.

The proposed system has far broader capabilities than even the best-equipped and trained rescuers. While the rescuer, if only, is capable of moving a short distance from the seal separating the space affected by a catastrophic event, the UV is able to plunge to considerable distances (even over 500 m) in sealed areas. The application of the UV makes possible carrying out measurements and acquiring images (video and infrared) and then transmitting them in real-time to the operator, enabling him/her to take more accurate, faster decisions concerning the manner of conducting further rescuing operations, or opening the space closed previously due to a catastrophic event.

Another innovative issue concerns the possibility of applying the UV to other inspections carried out in the main roadways not affected by catastrophic failures. These inspections could be performed on weekends, when miners do not work in the inspected space. An example might be the detection of early failures or overheating in equipment installed in mining roadways, such as conveyors etc. To this end, the UV can operate autonomously using the map of the space to be traversed into, and avoiding collisions with different kinds of obstacles and machinery lying on the floor. The UV collects data and stores it in a mass storage memory to allow for later analysis in a laboratory. Such an application of the parts of the system dramatically widens the usefulness of the UV and increases the proportion of time that it can be used for.

UVs of type similar to developed by the TeleRescuer consortium have been used only very rarely until now, and only to a limited extent in order to search and save the lives of miners in big mining disasters. Despite the fact that mobile robots have been around for a long time, their means of movement in such a complex environment - like coal mine roadways - after disasters, and problems with wireless communication systems, have meant that their practical application in this kind of difficult environment has been limited. Most noticeable was the lack of fully functional wireless solutions enabling intuitive, effective and remote (a communication range even greater than 500 m of the separating area from the dam up to a mining disaster site) inspection with the use of the UVs (e.g., robots) that can reduce the direct involvement of rescuers to a minimum.

2.4.2. Technical end economic potential for the use of results

The analysis of projects realised on the world reveal the need on the part of the European coal industry to increase the safety of miners and mine rescuers, the protection of mine infrastructure. This condition can be achieved by decreasing the number of the interventions by humans (especially rescuers) inside mines which, consequently, avoids harsh working conditions and increases safety.

During the years 2000-2009, in Polish mines alone there were 129 mining accidents involving rescuers working in extremely tough conditions. In these accidents, 122 miners were killed. For the years 1945-2008, 107 rescuers were killed in Polish coal mines [Source: K. Gadowska (ed.), *Rescue in coal mines. Determinants of technical, economic, organizational and social issues* (in Polish), Central Mining Institute, Katowice, 2011]. Accidents caused by gas explosions killed 29 mine rescuers (globally the highest), coal dust explosions killed 14, deadly levels of carbon monoxide killed six, and the absence of oxygen killed five. A common cause of death among rescuers was heat stroke, with 22 such cases. Suffocation due to lack of oxygen in the breathing apparatus was the cause of death of 17 people. Some rescuers were killed as a result of other accidents. During these 64 years, the accident rate was 1.6 deaths/year. The statistics presented omit accidents which did not cause rescuers' deaths but just bodily injury. They also omit rescuers' actions in less tough conditions, the number of which is much greater. In the case of mines in the EU, the number of accidents has been less than in Polish mines. However, outside the European Union the number of accidents is much higher, especially in the coal mines in China, Ukraine and Russia. The statistics show how important it is to reduce the number of deaths and serious injuries.

For several years, attempts have been undertaken to improve the safety and efficiency of the operation of human rescuers (presented above) with the use of specialised mobile robots. Only a limited number of specialist robots have been dedicated to improving safety in coal mines. These robots have mostly been developed outside the European Union (e.g., in China, the US and Australia). Several mobile robots have been developed for the detection of explosive or lethal gases, and for searching and rescuing trapped people after coal mine disasters. However, advances in the fields of robotics and mobile robotics over the last two decades have not yielded a sufficient solution in the form of a mobile rescue robot. Many important problems have not yet been solved satisfactorily.

The final result of the research project is a system with a very high potential for implementation. The results achieved substantial improvements in the area of safety in coal mines.

The strategic benefits in terms of the possibility of safely continuing the exploitation of European coal by carrying out inspections of the affected spaces significantly earlier and to a greater extent are a substantial improvement when compared with inspections performed by human rescuers (this will reduce times and financial losses), reducing to a great extent, or even eliminating the life and health hazards for rescuers who carry out the inspection of the closed spaces of a coal mine, and decreasing risk of subsequent catastrophes. These benefits are important, especially in the current geopolitical situation, where the prices of competitor energy sources are soaring, in addition to being supplied from politically unstable areas.

To reduce the danger for a rescuer, the Consortium solved today's problems and developed an efficient system (i.e., more efficient than existing solutions) that consists of an unmanned vehicle (UV) that is teleoperated or is able to operate autonomously, a reliable broadband communication system, and technology for the virtual teleportation (virtual immersion) of the rescuer to the area of operation (otherwise inaccessible due to critical hazard parameters), combined with a very realistic simulator. The proposed system with the UV as an important part allow the making of remote measurements and inspections of spaces inaccessible to humans in a highly intuitive and innovative way. The application of the proposed system by the Consortium should reduce the number of fatal accidents involving rescuers by about 80%. Therefore, the accident rate should fall to 0.3 deaths/year.

The Consortium estimates that the demand for this type of system in rescue operations is 20 UVs worldwide, including eight UVs in the European Union (~2 UVs per central mines rescue station in each country). Where the UVs are used for monitoring activities, the required number of UVs would be much higher. The cost of production of one system (the commercial version) can be estimated to be a minimum of 250,000 Euros. This amount can be related to the huge financial losses due to the downtime following catastrophic events. If we assume that a given mine produces 3,000 tons from one long wall of coal per day, and that a ton of coal costs 100 Euros, this gives us a daily loss of 0.3 million Euros. Therefore, the pay-back is almost instantaneous, in addition to the immediate safety increase in rescuer's work.

Summarising, there is a number of results of direct interest to the European coal industry, which contain:

- Remote inspection of areas affected by catastrophic events when conditions are not suitable for rescuers;
- Remote inspections of the affected areas more often than inspections performed by human rescuers;
- Producing and transmitting maps of spaces affected by catastrophes;
- Remote intervention for the diagnostics of underground mine infrastructure;
- Decreasing the risk of subsequent catastrophes.

2.4.3. Dissemination of results

In the framework of WP5, which was associated with the dissemination of the results, a strategy of dissemination and communication was elaborated. The responsibility of each partner in the project for the tasks connected with the dissemination was allocated. The following deliverables concerning WP5 were achieved: the official TeleRescuer logo, the official website (D.5.1), the template for multimedia presentations, the brochure on the main project's findings (D5.2), scientific publications (D5.3), a scientific seminar presenting the theoretical results (D5.4), a promotional seminar intended for the potential recipients of the project's results (D5.5).

- The official TeleRescuer logo

Logos are a critical aspect of business marketing and a face of each project. For this reason, a unique TeleRescuer logo was elaborated (fig. 5.5.3.1). The TeleRescuer logo is a graphical display of the project's unique identity, and provides essential information about this project. The logo was designed for allowing the customers to identify with the project core objectives. The elaborated logo consists of a combination of graphics and typographic. The TeleRescuer logo presents a rescuer, an unmanned vehicle with a symbolic representation of the teleportation process, and a word TeleRescuer. The TeleRescuer logo was used in advertising, all business marketing materials and official and unofficial documents.

Fig. 5.5.3.1 The official TeleRescuer logo

- TeleRescuer website

In order to disseminate the results of the project a project website was developed and published (fig. 5.5.3.2). This website is the first deliverable obtained in the framework of WP5: *D5.1 A TeleRescuer project official webpage*.

A TeleRescuer website was developed at the beginning of a TeleRescuer project realisation in order to disseminate the project. The TeleRescuer official website was designed taking into account "good practice" regarding to structure and contents of project websites, presented in document "*EU Project Websites – Best Practice Guidelines*". Every effort was made to setup this website as visible, legible and clear, and to publish the necessary amount of information. The website is visually attractive and informative, giving access to main sections that are expanded into subsections. The contents of website is regularly updated. The TeleRescuer website has efficient structure and accessibility. The website is divided into 8 main sections: Home (homepage), About TeleRescuer, Consortium, For media, News, Gallery, EC, Contact.

For the TeleRescuer website the following domains are used:

- www.telerescuer.polsl.pl;
- telerescuer.polsl.pl;
- www.telerescuer.eu.

The name of each domain contains the name of the TeleRescuer project. For this reason, they are strongly associated with the project.

Although the project has been completed, the website will be still published and updated in order to continuously promote the results.

Fig. 5.5.3.2 The official TeleRescuer Website (homepage)

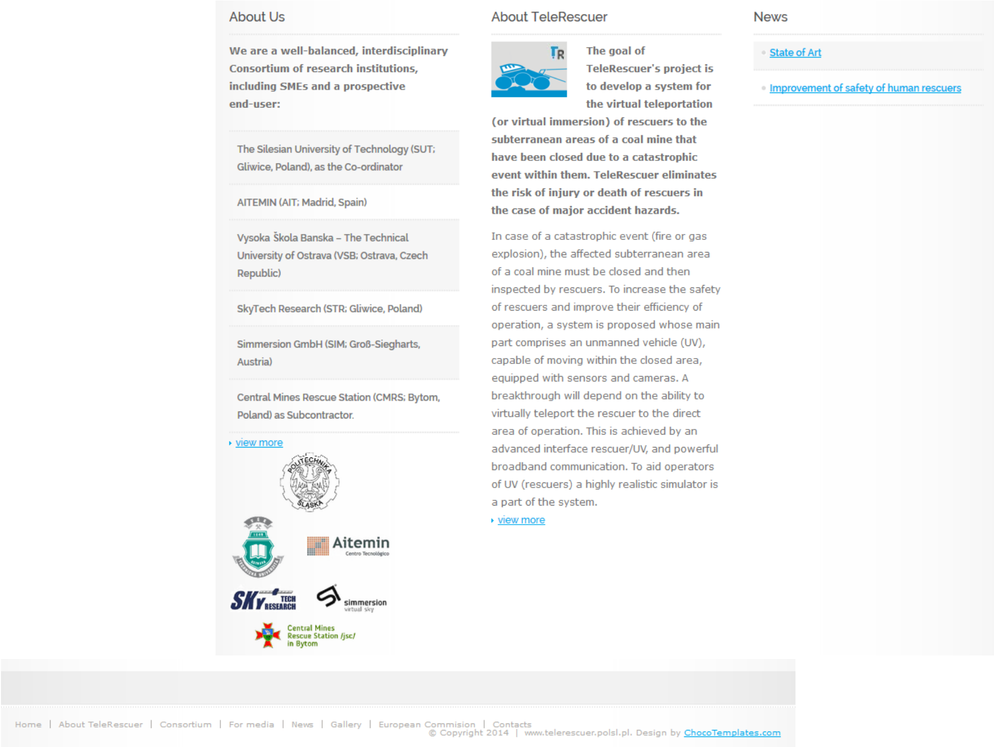


Fig. 5.5.3.2 (cont.) The official TeleRescuer Website (homepage)

- Scientific papers

22 scientific papers and posters related to the results of the project were prepared. The list of all papers is presented in Project overview table of this report.

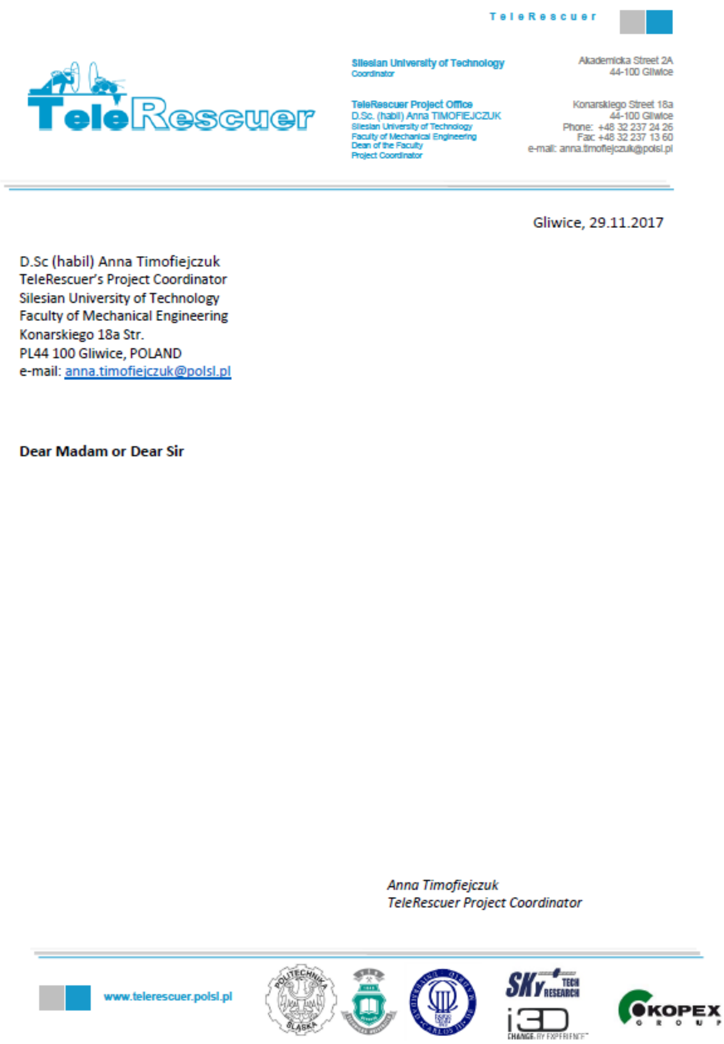
- Template for multimedia presentations

To enable the dissemination of the theoretical and experimental results achieved at different stages of the project, multimedia presentations generally were used. All the partners were responsible for preparing such presentations after completing their individual tasks. For this reason, in order to unify all presentations related to the TeleRescuer project a special template for MS PowerPoint was developed (fig.5.5.3.3). This template was used by all the partners from the TeleRescuer consortium during any internal (consortium meetings) and public (conferences, seminars, trade events etc.) speeches with the use of presentations.

Fig. 5.5.3.3. The official template for presentations

▪ Template of official and unofficial documents

To enable professional communication with partners interested in the results of the project, a consortium template for the project correspondence was developed. All the partners were responsible for using this template.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Dear Madam or Dear Sir

Anna Timofiejczuk
TeleRescuer Project Coordinator

www.telerescuer.polsl.pl

Fig. 5.5.3.4. An official template for documents

▪ Promotional brochures

The preparation and publication of thematic brochures (either in printed or in electronic form) on the project and the obtained scientific and utilitarian results (especially on the TeleRescuer system) was one of the main results of the work. At the initial stage of the TeleRecuer project, the concept of the first brochure was developed. In order to increase the attractiveness of the brochure, innovative techniques of augmented reality (AR) were used to present knowledge to interested recipients (eg. prospective clients). The augmented reality techniques enable the presentation of virtual content imposed on the real world in such a way that it looks like one environment. The brochure contained a special QR code, which enabled the installation of a special application for the visualization of the virtual content, e.g. 3D models of an unmanned vehicle, films, photos supplemented with a voice commentary.

Fig. 5.5.3.5. An innovative brochure with the use of augmented reality techniques and an example of its application

Later on, a standard information brochure was prepared with the main purpose for the fairs and meetings with people interested in the results of the project.


Fig. 5.5.3.6 A brochure with general information about TeleRescuer

- Scientific seminar presenting theoretical results

The organization of at least one scientific seminar was one of the main results of the work carried out in the dissemination of results. The seminar was organized on 04.12.2017 in Gliwice (fig. 5.5.3.8). During the seminar invited guests (representatives of science and industry) had the opportunity to listen lectures presented by members of the TeleRescuer project consortium. The seminar also included a demonstration of the TeleRescuer systems developed under the project. The seminar ended with a round table, where the guests had the opportunity to comment on presented project results. A detailed seminar program is presented in fig. 5.5.3.7. For invited participants of the seminar the organizer prepared advertising materials related to the project.

Moreover the Coordinator regularly (average one per month) organised webinars (videoconferences). During these on-line meetings theoretical and practical results of the TeleRescuer project were presented.

TeleRescuer

A SYSTEM FOR VIRTUAL TELEPORTATION OF RESCUER FOR INSPECTING COAL MINE AREAS AFFECTED BY CATASTROPHIC EVENTS

CONFERENCE

"TeleRescuer: A system for the virtual teleportation of rescuers to the area affected by the catastrophic event"

DATE: 04 December 2017

LOCATION: Towarowa 7 Street (Campus of the Faculty of Mechanical Engineering, SUT), PL44 100 Gliwice, POLAND

PROGRAMME:

09:00	9:15	Opening ceremony	A. Timofiejczuk
Chair: P. Olivka			
9:15	9:25	Genesis of the TeleRescuer project	W. Moczulski
9:25	9:50	General information of scientific and technical results	A. Timofiejczuk
9:50	10:10	TeleRescuer: Mobile robot as a remote sensor and system for acquiring data and images	M. Adamczyk
10:10	10:30	TeleRescuer: The control system	J. Babjak
10:30	10:50	Questions & discussion	
10:50	11:20	Coffee break; Presentation of the system components	
Chair: W. Moczulski			
11:20	11:40	TeleRescuer: System for 3D-mapping	P. Olivka
11:40	12:00	TeleRescuer: Oprator's interface of the system allowing virtual teleportation of the rescuer	D. Myszor
12:00	12:20	TeleRescuer: Subsystem for acquisition of data and images	B. Genoves
12:20	12:40	TeleRescuer: Telecommunication subsystems	B. Genoves
12:40	13:00	TeleRescuer: ATEX considerations	G. Mura
13:00	13:20	Questions & discussion	
13:20	13:50	Round table: further development and implementation of the TeleRescuer system	Moderator: K. Cyran
13:50	14:35	Lunch	

WWW.TELERESCUER.POLSL.PL

Fig. 5.5.3.7. An ivitation with a programme for the seminar

Fig. 5.5.3.8. A commemorative photo of the participants of the seminar and a photo during the selected presentation

- Participation in a fair

As part of the work related to the dissemination of results, the developed solutions were presented on The International Fair of Mining, Power Industry and Metallurgy in Katowice, August 29, 2017. The event is organized periodically by Polska Technika Górnicza S.A. (PTG), and is very popular among representatives of the mining industry (mainly) and national authorities, as well as visited by the Prime Minister of Poland and representatives of the Council of Ministers. As part of the exhibition, the mobile station of the unmanned vehicle TeleRescuer and the mobile platform with subsystems were presented. The stand was designed and made with the use of designed advertising materials - a wall of rollups (fig. 5.5.3.9, fig. 5.5.3.10). A brochure and gadgets have been prepared for visitors of the trade fair stand.

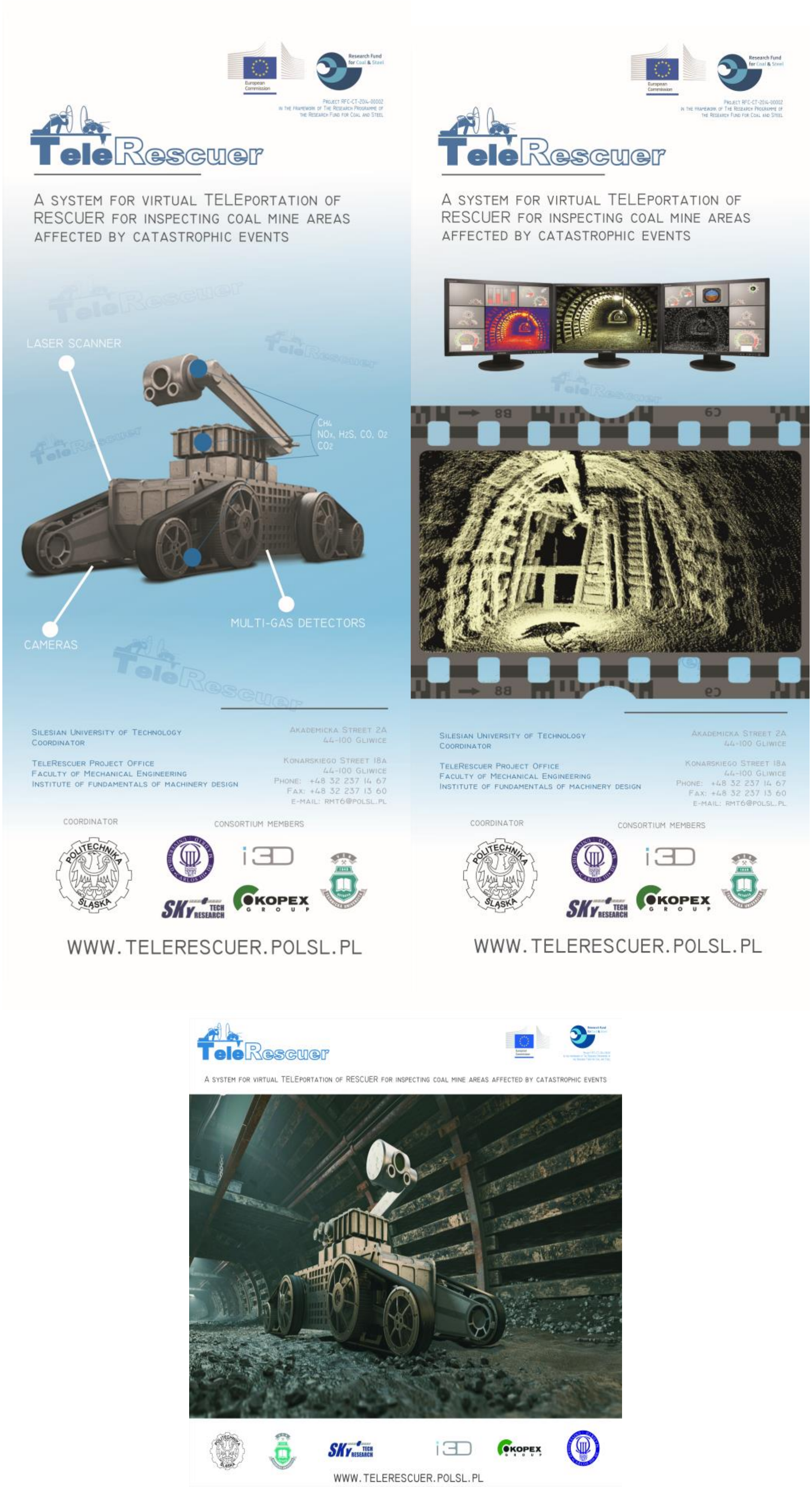

Fig. 5.5.3.9. Rollups developed for the exhibition stand

Fig. 5.5.3.10. Fair stand of the TeleRescuer project

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List of acronyms and abbreviations

ATEX	ATmosphères EXplosibles: Used usually to refer to the series of EC directives related with explosive atmospheres and related IEC/EN Standards.
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
LED	Light-emitting diode
LEL	Lower explosivity level
LoS	Line of sight
MCS	Main control system
MOS	Mobile operator station
MPS	Methane protection system
NLoS	Non-line of sight
O_2	Oxygen
SM	Survey Monkey
SOS	Simulator operator station
UV	Unmanned Vehicle

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The goal of the project was to develop a system for the virtual teleportation (VT) of human rescuers to the subterranean areas of a coal mine that have been closed due to a catastrophic event that occurred within them. Nowadays, human rescuers inspect such areas facing extreme dangers. They may enter the restricted area if values of several critical parameters achieve acceptable levels, which often takes a long time. To overcome these problems and improve the efficiency of operation of human rescuers, a TeleRescuer system was developed. It takes advantage of a special unmanned vehicle (UV) capable of moving within the area affected by the catastrophic event. The UV is equipped with sensors and video cameras (standard and IR). A breakthrough in the operation of such UVs depends on the VT of the rescuer to the area of operation, which is achieved by combining three key technologies. First, particular attention is paid to the rescuer/UV interface that allows direct action in the inspected area while the operator remains in a safe place. Second, to allow the VT, a very powerful communication system was developed capable of broadband broadcasting of videos, results of measurements, and control of the UV, its sensors and effectors. Third, a simulator was developed allowing for testing the interface and for training rescuers in controlling and using the UV during the rescue operations in a representative environment. The general approach and the system itself were tested in a relevant environment under supervision of the Central Mine Rescue Station.

Studies and reports

Publications Office