European Land Robot Trial (ELROB)

Towards a Realistic Benchmark for Outdoor Robotics

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***Abstract* — The European Land Robotic Trial (ELROB), which was held for the fifth time in 2010, is designed to compare unmanned ground vehicles in realistic outdoor tasks. It addresses the need to create a benchmark that can reproducibly compare and evaluate different robot systems. While robot trials like the DARPA Grand Challenge or the RoboCup have proven to be adequate benchmarks to compare robots systems in specific scenarios, the ELROB provides benchmarking in a wide range of tasks, which are oriented at prospective use-cases from a large variety of applications. In this paper we describe the ELROB 2010, the rationale behind the scenario design and how the trial has been implemented. We present the benchmarking system used to evaluate the robots' performance in the different tasks and, finally, have a closer look at some exemplary results.**

***Keywords* — robot contest; outdoor; benchmark.**

I. Introduction

The European Land Robot Trial (ELROB) was designed to demonstrate and compare the capabilities of unmanned systems in realistic scenarios and terrains. It was founded by the European Robotics Group and is organised by the Fraunhofer Institute for Communication, Information Processing and Ergonomics (FKIE), formerly part of the Research Establishment for Applied Sciences (FGAN). The trial is held annually, alternating between a more military and a mainly civilian focus. Up to now, the so-called M-ELROB was held at the military school in Hammelburg, Germany, whereas the civilian C-ELROB is performed at changing locations throughout Europe.

One major aim of the ELROB is to get a deep insight into the field of ground robotics by testing existing solutions in practical trials. These trials are conducted with a focus on short-term realisable robot systems and are designed to assess current technology while solving real world problems. Thereby, scenarios are not limited to the abilities of today's robots, but focus on realistic missions demanded by experienced users in difficult environments.

The ELROB presents a variety of realistic user defined tasks. These tasks include, for example, security missions, convoying, or reconnaissance by day and night. Although robotic contests are widely accepted as valuable means for benchmarking real outdoor robot systems, it is generally a difficult task to compare results from different contests or to generate a reasonable ranking even within one of the quoted scenarios. Omitting all details of task design, it is still obvious that many different parameters might have an influence on the overall benchmark for a mission. Taking the convoying scenario as an example, average speed, totally driven distance, or degree of autonomy are only one possible choice from a wider range of feasible parameters. Each parameter has to be measured in a precise and reproducible manner, which often raises serious problems, and afterwards has to be weighted in its influence on the final benchmark.

This paper will mainly address the latest ELROB, which took place from 17th until 20th of May 2010 in Hammelburg, Germany. We present the rationale behind the scenario design, the special demands of the co-organising military user, and the structure of the participants. After a detailed description of the different tasks of ELROB 2010, the remainder of the paper deals with the chosen benchmarking approach, thereby discussing the typical problems in the field of ranking systems, namely choice, measuring, and weighting of the different benchmark parameters.

II. Related Work

Generally, it is a difficult task to compare different published approaches in the field of robotics [1]. Thus, robot competitions are recognized as valuable benchmarks for real robot systems [2]. Several different competitions were held in the last years. Two of the largest and best-known competitions are the RoboCup [3] and the DARPA Grand Challenge [4], which are also recognized outside the robotics community.

While the RoboCup is currently targeted at indoor robots, the DARPA Grand Challenge aims to test and compare driverless cars. It started in 2004 with the rather simple task of following a 241 km long path, defined by several thousand UTM waypoints. Due to the difficult terrain and some teething problems, no participant was able to solve this task. In 2005, the task remained basically unchanged, and four participants successfully completed the race. In 2007, the DARPA Grand Challenge modified its goals from driving autonomously on difficult terrain to interacting with other vehicles in an urban scenario. Three teams could solve this very demanding challenge.

The ELROB is somehow comparable to the DARPA Grand Challenge in its attempt to gauge the functionality of outdoor robots. However, as already mentioned the ELROB presents a wider choice of user defined tasks instead of only one single scenario. Different users often express completely different requirements and specifications for robot systems depending on the possible fields of application. Instead of combining demands into one large scenario, like in the DARPA Grand Challenge, it might be more meaningful to have different tasks, which correspond to the various application scenarios. The following chapters present an exemplary description of the tasks for ELROB 2010.

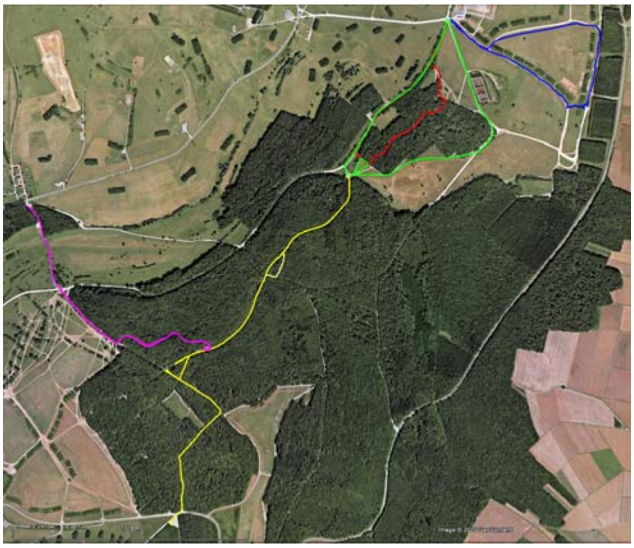

Figure 1. Overview of the movement oriented trials of ELROB 2010. The yellow track belongs to the approach part of the reconnaissance scenario, the purple one marks the mule scenario, the green, red, and blue tracks correspond to the different levels of the transport trial.

III. TRACKS AND TRAILS

The chosen area for ELROB 2010 lies within the training facility of the German military school in Hammelburg. Its size is of about nine square kilometres. The accessible roads have different qualities, ranging from well paved to heavy dirt roads. The environment is predominantly woody.

The different tracks on site were chosen to test specific aspects of robot deployment. Some challenges were common to all tracks; others were specific to certain scenarios. In preparation for the trials, every track was tested with respect to

- accessibility of the roads and paths,
- GPS reception, and
- radio reception between vehicle and control station.

By selecting areas with an elevation profile that does not support continuous radio communication from the control station, a certain level of autonomy was enforced. Thus, it was deliberately made difficult or even impossible to complete the missions in a purely remote-operated way.

Generally, the trials of ELROB 2010 have been divided into two major categories. On the one hand, there were scenarios with a focus on driving large distances of up to several kilometres. Due to the long distances in combination with the already mentioned hilly and woody character of the environment, it could be expected that solutions with a large degree of autonomy would perform best. Figure 1 presents an overview of the whole area. The different colours mark the different tracks and missions. In the following subsections, each scenario will be briefly described.

The second group of scenarios, on the other hand, had its focus on reconnaissance tasks. In these trials the robots had to search a given area, consisting of streets, paths, houses and grassland, for different kinds of targets, for example explosives, chemical or toxic waste, and radiation sources. Besides autonomy, other factors like manoeuvrability and a well-equipped sensor platform were of greater importance for this kind of tasks. The robots had to pass stairs and enter rooms through narrow doorways in order to reach all targets. In addition, although all targets could be seen with normal camera systems, additional hints like acoustic signals, heat or radiation sources had been installed for an easier identification. Therefore, systems with good sensor equipment had significant advantages during these trials.

Figure 2 illustrates some aspects of the reconnaissance scenarios. The leftmost picture shows a major part of the target area for these scenarios. From their starting point, the vehicles had to go there along some given, UTM-defined route. In the target area, open grassland with any kind of barricades, barriers or blockades had to be passed and different kinds of houses had to be entered and inspected. The middle picture presents an example target for the RSTA mission and the right one shows an exemplary radiation source in the NBC scenario. The details of the missions like the distances to be travelled and the exact kind of targets to be identified will be described in the following subsections.

A. *Movement Transport Trial*

Goal of this trial was to implement some kind of stable convoying in an outdoor, non-urban and off-road terrain with roads and paths ranging from asphalt streets to simple dirt roads in the forest. The convoy consisted of two vehicles of which only one was allowed to have a human driver. The second one had to be autonomous. The required path was defined by a small set of UTM waypoints, which were quite far from each other, so that the robot could not just drive straight lines between the waypoints but had to navigate along the roads and paths. The roads were part of the local testing ground for trucks, usually gravelled and led mainly through the forest. They were not marked, so mostly there was no clear distinction from the surrounding terrain. Sharp turns, dead ends and narrow passages occurred at several positions. No team member was allowed to inspect the trial area in advance.

The whole trial was divided into three levels of increasing difficulty, each consisting of a round trip with one common starting point. Looking at figure 1, one can identify the starting point at the connection of the green and blue track. The green track was the easiest one. The vehicles could use wide, well-paved roads, only with some very sharp turns to prove the robustness of the convoying algorithm. For the second level, a part of the original green route was replaced by a small dirt road in the forest; see the red track in figure 1. Level three, the blue track, was part of a special "off-road" truck testing site.

Figure 2. Illustration of the reconnaissance scenario of ELROB 2010. Left part – picture of the surroundings, streets, paths, houses, and grassland. Middle part – an example target in the RSTA trail. Right part – an exemplary radiation source in the NBC scenario.

Due to the very demanding character of this route and in contrast to the normally applied rules, the teams were allowed to have a look at the track in advance, in order to prevent possible harm from their vehicles. Each level was about 2.5 kilometres in length; the maximum time for completion of this trial was one hour.

B. Mule Transport Trial

The objective for this scenario was to let a vehicle serve as a “mule” and carry as much payload as possible between a loading and a turning point. Again, the terrain was woody and hilly with – partly very steep – roads of different quality. Instead of getting the UTM coordinates of the turning point directly, the robots had to follow a human who guided the vehicle from the loading point to turning point once. To simplify the mission for the teams this leader could be one of the team members, who himself was then led by someone from the organizing personnel. Thus, the leader from the team could wear, for example, specially coloured clothes or use special gestures.

After reaching the turning point for the first time, the robot had to shuttle the payload between the two points as fast and as autonomously as possible. In figure 1, the mule track is marked in purple. It was not known to any team member in advance. The distance between loading and turning point was about two kilometres; the maximum time for completion of this trial was one hour.

C. Reconnaissance Trial – Approach (Day/Night)

In contrast to last years’ approach, for ELROB 2010 the reconnaissance mission was split up into two independent parts. In the last years the objective was, first, to let the robot approach through unknown terrain into a designated target area and, second, search this target area for special, pre-defined targets. As already mentioned in the introduction for this chapter, the nature of these two subparts of a classical reconnaissance mission is rather different. The first part is more suitable for larger platforms with good and autonomous driving capabilities, whereas in the second part normally smaller robots with good manoeuvrability and special sensor equipment normally perform better. Consequently, nearly no participant was able to fulfil the complete trial during the former ELROB contests. Therefore, the organisers decided to separate the approach from the search in the target area.

Objective of the approach part of the reconnaissance scenario was now to reach a target point about three kilometres away. At that target point, an overview picture of a closely visible village should be taken. On its way towards the goal point, some intermediate waypoints had to be traversed. All these points were defined by their UTM positions. The yellow track in figure 1 marks one possible route for the approach, which passes all these intermediate waypoints. However, theoretically, the robots could choose their way freely. The track consisted of several narrow passages and even two dead ends, which can be identified by the small detours in figure 1. The area was completely woody and rather hilly, which notably complicated any attempt to maintain radio connection. The roads mainly consisted of forest paths with no clear distinction from the surroundings. As usual, no team member was allowed to inspect the area in advance. The maximum time for completion of this trial was one hour. The whole trial was first conducted under normal daylight conditions. The most successful teams had the chance to repeat the identical mission during the night.

D. Reconnaissance Trial – Target Area (Day/Night)

The terrain for the reconnaissance missions in the target area was an urban area within a valley. The urban area consisted of small buildings and homesteads, which are spread sporadically over the grassland of the valley (see left picture of figure 1). The buildings were connected with small roads and footpaths. Barricades, barriers and other blockades occurred at several places. From their starting point at the border of the valley the robots had to move along a given, UTM-defined route into a specific target area about 300 metres away. The relevant area for inspection was defined by a set of UTM boundaries. As for all other missions, no inspection of the operational area was allowed in advance. The maximum time for the completion of a trial was one hour.

The participants could attend up to three different kinds of such reconnaissance missions, according to their specific sensor equipment. The main difference between these possible missions was the type of targets the robots had to search. In the more general “reconnaissance, surveillance and target acquisition” (RSTA) trail, targets could be suspicious persons and vehicles, weapons, barricades and blockades, but also special acoustic signals like weapon fire or agitated discussions or heat sources, for example from vehicles or fires. The middle part of figure one gives an example. Those numbered orange cones marked all targets. The letters on the small white sheet in the middle of the picture should have been readable in the images acquired by the robot. Some of the targets could be only acquired from distances of up to 500 metres.

The “nuclear, biological, and chemical” (NBC) reconnaissance scenario required special sensor equipment, because there was no distinct marker for the targets like the orange cones in RSTA. Instead, the special physical or chemical properties of the – simulated – chemical agents, toxic industrial chemicals, radiation sources or explosives had to be measured. Finally, during the “explosive ordnance reconnaissance” (EOR) mission the robot had to inspect along a pre-defined UTM route. The robot had to search for suspicious objects like possible Improvised Explosive Devices (IED), ammunition, explosives, or wires under, beside or on the road, but – of course – without touching them. For all three types of missions, imagery and exact position of each target had to be acquired and transmitted to the control station.

IV. PARTICIPANTS

Ten teams in total participated in ELROB 2010, six teams came from European universities and four participants were from German and US industry companies. This section will shortly introduce their robots and vehicles.

The Institute of Real-Time Learning Systems of the University of Siegen took part with the robot AMOR. AMOR is a modified quad equipped with laser line scanners, PMD cameras and a stereo camera system. It uses a 3D environment model and fully featured local and global maps to drive autonomously, for example to follow a person or to pass given waypoints [5]. The Real Time Systems Group (RTS) of the University of Hannover participated with a robot called HANNA. Based on an off-the-shelf transport car, HANNA is equipped with various sensors for tele-operation, semi-autonomous operation and fully autonomous operation. The main sensors are two 3D laser range scanners used for environmental perception. In addition, multiple cameras, Differential-GPS, and inertial sensors are used for vehicle control. The Robotics Research Lab of the University of Kaiserslautern attended with their Robust Autonomous Vehicle for Off-road Navigation (RAVON). It is able to move fully autonomously, driven by a behaviour-based control system. It uses three 2D laser scanners and two custom-built stereo camera heads, as well as several additional sensors like GPS or a magnetic field sensor for localization purposes [6].

The Team MuCAR from the University of the Bundeswehr Munich (UBM) developed and operated the robot MuCAR-3. It is a modified Volkswagen Touareg, which allows computer control of steering, brake, throttle, and automatic gearbox. The team focuses on use of a Velodyne 3D laser scanner. The high definition 360 degree Laser Scanner is mounted on the roof of the vehicle. The RoboScout Team of the company BASE 10 SYSTEMS Electronics took part with the large robot GECKO. It is a four-wheel driven vehicle of about 3000 kg. Its speciality is its high manoeuvrability, because of its four separately steerable wheels. The robot can be controlled can be controlled via satellite or terrestrial communication, and can use a special small airplane as a relay station. The company Telerob presented their robot teleMAX. It is a track robot with flippers and a robotic arm. It is equipped with several cameras and is able to climb stairs. The team of Università degli Studi di Catania used a track driven vehicle that is used as an experimental research platform for volcano inspection. For autonomous navigation, the system is equipped with stereo camera-system, IMU, GPS and a SICK laser scanner.

The University of Versailles used a new and self-developed robot. The team is based on a student project that used a commercial electro kid quad as chassis for the robot. While moving, the environment is perceived through a laser range finder, sonars, infrared thermal sensors and webcams. The project addresses searching and rescuing people after natural disasters such as earthquakes. The company MacroUSA attended with a small Teleoperated UGV. The vehicle is equipped with a COFDM based vision system delivering a 360-degree view using three cameras. For navigation a GPS, IMU and a compass are included. However, the vehicle is not design to operate autonomously. The company ELP presented the PackBot, which was originally developed by IRobot. The tele-operated robot came in a basic version having on board only a camera and a manipulator.

V. RESULTS

For the presentation of the results of ELROB 2010 and for the discussion of our benchmarking system we will consider only a subset of all the conducted trials. As already mentioned during the description of the scenarios, the trials could be divided into two categories, one that focuses on autonomously driving large distances and the other one that more concentrates on steering capabilities and specialised sensor platforms. Since from our point of view this first kind of missions is the more interesting and more important one for the robotics community, we will omit the results for those scenarios dealing purely with reconnaissance in the target area. Additionally, it can be stated that actually all vehicles in those trials acted fully tele-operated and none of them was equipped with any special sensor equipment apart from (high-resolution and sometimes heat image) cameras. A detailed examination of all omitted trials – including the missions at night – can be found at [7].

TABLE I. WEIGHTS OF THE RELEVANT MISSION PARAMETERS

	Transport Movement	**Transport Mule**	**Recon. Approach**
Degree of autonomy	1000	1000	1000
Total distance	100	--	100
No. of round trips	--	100	--
Total runtime	10	--	10
Delivery of digital map	1	1	1
Delivery of GPS log file	1	1	1

The evaluation of the remaining missions – the mule transport trial, the movement transport trail, and the approach part of the reconnaissance trial – concentrated on parameters which were clear to distinguish and easy to measure. Table I gives a short overview:

- Movement Transport Mission
  Degree of autonomy, total distance driven, total runtime, delivery of a digital map and a GPS log file of the vehicle's track.
- Mule Transport Mission
  Degree of autonomy, number of successfully completed round trips between starting and turning point, delivery of a digital map and a GPS log file.
- Reconnaissance Mission – Approach
  Degree of autonomy, total distance driven, total runtime, delivery of a digital map and a GPS log file.

Obviously, autonomy was of overwhelming relevance to achieve a good result. In contrast to the other influencing factors, for which it is clear how they can be counted or measured, our definition of autonomy has to be explained. We used the ratio of total driving time and the so-called "manual interaction time", which starts at the moment when anyone interacts in any way directly with the vehicle or, for example, via an operation console. It ends in the moment when this interaction is over and the vehicle continues its autonomous work. The measurements for all the influencing parameters are normalized into the range [0; 1] and afterwards multiplied by the factors from table I, leading to a team's total sum for each mission.

A. Movement Transport Trial

Unfortunately, the movement trial suffered from very heavy rain. Due to the weather conditions, two of the registered teams, the University of Kaiserslautern and the University of Hannover, withdraw their participation. The University of Siegen and their robot AMOR managed the easiest first track without problems and could follow the leading car without any necessary interaction at an average speed of 5.8 km/h. However, at the rougher terrain of the second level the robot had considerable problems and often had to stop. As a result, the maximum trail time of 60 minutes ended after about 1200 metres of the second track.

The MuCAR-3 from the University of the Bundeswehr Munich performed very well and completed the first two levels of the trial at an average speed of 14 km/h and without any intervention of their safety driver. The team tried – without evaluation – even the very demanding third level and finished it with only one necessary stop. The third and last participant, the robot GECKO of the company BASE 10, also managed the easiest first track, but with some interaction, especially at sharp turns. Afterwards, the team aborted the mission because they feared damage for their vehicle due to the expected worse road conditions in the next levels.

Before looking at table II for the numerical results of this trial, it is important to mention, that the MuCAR team regrettably could not be evaluated because their mission setup was not compliant to the rules of ELROB 2010. For safety reasons they insisted on a human driver inside their car, who had to observe and – in case of need – control the actions of the robot. Therefore, the team started out of evaluation. As a result, official winner of this scenario was the University of Siegen, followed by the GECKO of BASE 10.

TABLE II. RESULTS OF THE MOVEMENT TRANSPORT TRIAL

Team	Robot	Result	Rank
University of Siegen	AMOR	1011	**1.**
BW University of Munich	MuCAR-3	n.e.	n.e.
BASE 10 SYSTEMS	GECKO	648	2.
University of Hannover	HANNA	n.p.	n.p.
University of Kaiserslautern	RAVON	n.p.	n.p.

B. Mule Transport Trial

The mule scenario started with the robot RAVON of the University of Kaiserslautern. Unfortunately, the team had technical problems, which forced the robot to stop after only a few metres. The second participant, HANNA of the Hannover University, successfully managed to follow its human leader and reached the turning point without larger problems. During the following autonomous shuttle mission, the robot had problems reaching the starting point again due to some technical faults. Shortly before the trial time was over, the team had to give up, only a few metres before arriving at the starting point again. However, corresponding to the benchmark parameters and since the vehicle was running autonomously most of the time, this result lead to the first rank in this scenario.

The University of Siegen and their robot AMOR reached the second place with a slightly worse performance. For a shorter totally travelled distance of about 2600 metres, the team needed longer and more frequent manual interaction with the system. The GECKO of BASE 10 SYSTEMS only drove a few hundred metres and then lost its way in the forest. Table III shortly presents the results of the mule transport trial. The team of the Munich Bundeswehr University was not evaluated for the same reasons as explained in the last section. Nevertheless, it is worth mentioning that the MuCAR-3 managed to shuttle between starting and turning point several times nearly without any intervention of the safety driver.

TABLE III. RESULTS OF THE MULE TRANSPORT TRIAL

Team	Robot	Result	Rank
University of Kaiserslautern	RAVON	206	4.
University of Hannover	HANNA	1000	**1.**
University of Siegen	AMOR	561	2.
BW University of Munich	MuCAR-3	n.e.	n.e.
BASE 10 SYSTEMS	GECKO	383	3.

C. *Reconnaissance Trial – Approach*

The scenario design for the approach part of the reconnaissance mission required a high degree of autonomy, because the very hilly and woody terrain made a permanent radio connection between vehicle and control station nearly impossible. Nevertheless, two teams tried to run fully tele-operated by using a fibre optic cable. The first of them, the company Telerob with their small robot teleMAX, reached the first dead-end about 500 metres away from the starting point. While trying to turn it cut the cable, which meant an immediate end of the trial. The GECKO of BASE 10 Systems performed better, because after the loss of the fibre optic cable it made use of the special radio relay airplane for transmitting the signals. However, due to the nature of the benchmarking system with its special emphasis on autonomy, it is clear that a tele-operated approach could not lead to good rankings.

The University of Kaiserslautern had to withdraw the participation because of technical problems with their robot RAVON. The remaining teams, the University of Siegen with the robot AMOR and HANNA from Hannover University, both tried an autonomous approach. AMOR only moved about 600 metres and then stopped due to some problems with a very steep forest path. When trying to free the robot, it unfortunately had a complete system crash. HANNA and the team from Hannover autonomously reached a distance of nearly two kilometres, but then faced some serious orientation problems. Since the team had no means of communication between the vehicle and its control station over this far distance, it had to give up at this point. Accordingly, table IV reflects the results of this trial. HANNA was the winner, and the University of Siegen reached a second place, although the GECKO drove faster and further, because of their autonomous approach.

TABLE IV. RESULTS OF THE APPROACH PART OF THE RECONNAISSANCE TRIAL

Team	Robot	Result	Rank
Telerob	teleMAX	368	4.
University of Siegen	AMOR	877	2.
University of Kaiserslautern	RAVON	n.p.	n.p.
University of Hannover	HANNA	1005	**1.**
BASE 10 SYSTEMS	GECKO	374	3.

It should be obvious, even through this very broad overview on the results of ELROB 2010, that the presented benchmarking system can be considered as fair only with regard to the special requisition of autonomy. Looking at the contest with a slightly different accentuation – for example on manoeuvrability, velocity or sensor equipment – immediately leads to different results. An appropriate extension and modification of the weighting parameters in table I might change the resulting ranks completely. Thus, it is important to keep in mind that a benchmark for robotic contests only reflects the organisers' demands and cannot reflect a robot's general suitability for outdoor robotic tasks.

VI. CONCLUSIONS AND FUTURE WORK

A. *Conclusions*

The purpose of ELROB is not to get an overview over technological possibilities but to test outdoor ground robots in real world scenarios without regard to current limitations of these systems. Thus, the scenarios had to show the gap between desired and possible applications for today's robots. As could be expected, not every participant could cope with the designed missions. So the results were not unexpected and definitely not disappointing. In retrospect, two main problems could be singled out – reliable hardware, including reliable communication, and innovative autonomous software controller.

It is noticeable that while the industry generally had hardware in excellent quality available, they lacked the innovative autonomous control algorithms developed by the university teams. On the other hand, the university teams had most of their problems due to their restrained hardware budget and the required trade-off between functionality and cost. The combination from the robots used by industry and state-of-the-art control algorithms developed at universities might achieve much better results.

B. *Future Work*

From the 20th to the 24th of June 2011, the sixth European Land Robot Trials will take place in Leuven, Belgium [7]. The current working title is "Robotics in Security Domains, Fire Brigades, Civil Protection, and Disaster Control". Therefore, the missions will be designed having typical scenarios of those fields of application in mind. Again the trials will be designed to present scenarios as close to real world applications as possible.

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