# Eurathlon 2013

## Scenario Application Paper (SAP) – Review Sheet

**Team/Robot** Team E15
**Scenario** Mobile manipulation for handling hazardous material

For each of the following aspects, especially concerning the team's approach to scenario-specific challenges, please give a short comment whether they are covered adequately in the SAP.

*Keep in mind that this evaluation, albeit anonymized, will be published online; private comments to the organizers should be sent separately.*

### Robot Hardware

The vehicle is a 4.9m long vehicle based on a ford explorerII. The vehicle is designed for search and rescue but really focused on transportation. The vehicle is fully autonomous. The vehicle cannot operate indoors and is not able to climb stairs but can cope with rails.

### Processing

Based on a number of industrial PCs and an i7 with CAN bus for communications. Ability to process a number of sensors including laser, 15 video cameras (!), IR and Lidar.

### Communication

2.4GhZ wireless Lan. Ability to start and stop the vehicle through wireless as well as emergency stop button.

### Localization

Based on IMU and GPS and odometry. Ability to build a map and use it for navigation (road recognition). Unclear if the vehicle uses SLAM.

### Sensing

Laser, Cameras, LIDAR, GPS, IMU. Basically, a very large set of sensors to be fused. The I7 acts as a fusion engine. Ability to detect targets using cameras.

### Vehicle Control

Fully autonomous but based on waypoint following. Unclear how new waypoints are generated on the fly. Can also detect objects and loads them autonomously onboard.

### System Readiness

System designed by a large group of experienced students. The system claims to reach TRL7 but I think it is closer to TRL4/5. The system is not fully complete yet but has potential. The details provided in the SAP are not always relevant to validate the actual ability of the robot.

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**Overall Adequacy to Scenario-Specific Challenges**

The vehicle would be more appropriate for scenario 4. In Scenario 2, the arena is likely to be small and the vehicle will have to perform complex manoeuvers to get to the targets. I am not convinced this will be safe and need to be evaluated. The TRL level is also a question mark as the system is still in development. The system will be fully autonomous and this will present H&S risks to be assessed by the judges.

Hochschule Esslingen
University of Applied Sciences

# euRathlon 2013

# Team E15 - Mobile manipulation for handling hazardous material

*Scenario Application Paper*

**Figure 1 E15 without batteries and generator in the workshop**

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## 1.0 Abstract

E15 is an autonomous vehicle built by students studying at the university of applied sciences Esslingen. The vehicle is based on the frame of a Ford Explorer II XLT, which got a completely new case. The motor was changed to a powerful electric engine and E15 can now be equipped with batteries or a generator, depending on the case of use. E15 is completely optimized for transportation, search and rescue missions and the exploration of unknown, non-urban areas in rough terrain. Sensors, bus systems and electronics were chosen to comply with lectures at the university of applied sciences Esslingen.

## 2.0 Team E15

The Team E15 consists of 32 students, studying at the university of applied sciences in an age between 19 and 27. Twenty eight of these students are studying computer engeneering in higher semesters, and were all listening to lectures like image processing, signal processing, computer architecture, embedded systems software design, car ECU design and similar lectures. The other four students are students of mechanical engeneering, innovation management and vehicle engeneering.

The system designers and the leaders of each sub-team are all experienced with autonomous vehicles. The team leader is an experienced designer and builder of autonomous systems such as autonomous snow plows, autonomous lawnmowers, autonomous desk dust removement devices and autonomous wheelchairs (Sicherheitstechnik und erweiterter Komfort für Rollstuhlfahrer, Jugend forscht 2007). Four of the team members have an emergency services background, the team leader is firefighter at the fire department of Reutlingen since 2006.

The team leader, the proxy and four other students are also working as student employees at bosch, in different departments that are concerned with reliability testing.

This team is kindly supported by Prof. Dr. Melcher (electrical engeneering), Prof. Dr. Keller (bus systems), Prof Dr. Friedrich (image processing), Prof. Dr. Marchtaler (sensor fusion), Prof. Dr. Koch (math and algorithms), some alumni (testing area, technical consulting, financial support) of the university of applied sciences and a lot of kind sponsors (financial support and sensors).

## 3.0 The Vehicle

E15 is a prototype vehicle, based on a commercial ’96 Ford Explorer XLT.

The body was removed completely and replaced by a new body, especially designed for transportation and search and rescue tasks. The overall length is 4,9m, the width is 1,6m and the height is 2,4m at a weight of about 1.8 Tons.

The original motor was replaced by an electric engine, the steering was replaced by an electrical power steering which can be controlled via CAN. The breaks can now be activated electrically by using a combined ESP/ABS ECU, which is also controlled using CAN.

The break, the parking brake and the motor control are equipped with a fail save mechanic, which automatically stops the vehicle in case of emergency using also the motor to stop the vehicle.

E15 has an exchangeable power supply. Depending on the desired time of operation, batteries or a generator can be mounted on the back of the vehicle. The power supply can be exchanged in less than two hours.

The Ford Explorer frame with four wheel drive, the automatically locking front- and rear differentials, the mud terrain wheels and an extended ground clearance combined with the special body are able to handle rough terrain such as mud roads, fields, snow, gravel or sand. This also enables the vehicle to navigate through debris or scrap, and drive over obstacles with a height of about 22cm without any problems. Carrying the maximum payload of about 650kg, E15s maximum climbing angle is about 43°.

E15 is not designed for indoor operation such as search and rescue inside an urban structure. Its main aim is the exploration of unknown areas, the transportation of equipment and injured persons and firefighting in underground structures.

Therefore, E15 is also equipped with special mounting points for stretchers (DIN 13024 N), Firefighting equipment for automated structure cooling (2 CM nozzles complying DIN EN 15182-3 externally supplied) and several mounting points for carrying devices and towing ropes.

E15 is not able to climb stairs or move inside a house.

The use of a commercial electrical power steering with a power of 1.4kW, a waterproof housing for the main electronic parts and the use of waterproof cases with special wipers for each sensor make the sensors insensitive for water and mud. The Radar sensors are also equipped with special heating caps to remove ice which could irritate the sensors.

For safety reasons, E15 is equipped with 2 emergency stop switches on each side, on the front and the rear of the car, and one beside the passenger seat. In case of system failure, the emergency stop functionality can be activated by pressing one of the e-stop switches, or activating the remote e-stop which is connected to the vehicle via redundant W-LAN (for more information, see “Communication”).

E-stop will stop the vehicle immediately using the brakes, the park brake and the motor brake, and deactivates the power supply to the motor. It also forces a reboot of the server, all the cluster controllers and the sensors.

Starting the vehicle at hills or close to obstacles which can only be climbed at maximum load is no problem.

## 3.1 Processing

The sensors are organized in clusters, containing sensors of the same type near the same position. Those clusters have the same cluster controller, which reads and collects the sensor data. This controller provides also information about the position of the sensors. The data is transmitted to the server using CAN (ISO 11898).

In case of the ultrasonic sensors, the gas sensors and the other sensors with low complexity, the cluster controller is an STM32F407, while the computer vision system, the LIDAR sensors and the radar sensor have two own industrial computer system.

The server for sensor fusion and mapping is an i7-3610QE on an Advantech AIMB-273 mainboard with 8GB ram and a compact fast drive with 16GB. This server communicates with the cluster controllers using CAN, if they are microcontroller based, and with the computer based cluster controllers using a redundant LAN connection, the motor controller, robot arms and the steering are connected to the server using a separate CAN.

This structure allows big distances between the different sensors and the server.

Image processing is done on several commercial industrial PCs using C++ and openCV. The obstacle and road data is transmitted to the server via sockets using vectors. All the computers are running RTOS in the competition, but there are also experiments with Arch Linux just for testing.

The target data and other relevant data such as mission information, mode of operation and waypoint data can be submitted using a simple PHP form, using the onboard computer system or connecting to a socket using the W-LAN connection.

## 3.2 Communication

The vehicle is operated completely autonomous, so the communication to a specific control station is only needed to start the vehicle at the beginning of the competition and get the collected data at the end of the competition. If the vehicle is in range, it can be controlled manually by an operator.

E15 and the control station are both equipped with a standard WLAN AP (Hirschmann BAT 54 F, IEEE 802.11a/b/g/h/i ), which is connected to a redundant LAN switch(). Every single connection is redundant (PRP). Two independent wireless channels, two CAT6 cables, two LAN interfaces on each device. Switch and AP are certified according to EN 61000-6-2, EN 61131 for use in automation anvironment; E1 certification for use in vehicles; EN50155 for use in trains and are tested for salt spray according to DIN EN 60068-2-52.

The car usually just listens for start, pause or stop commands or target information. In autonomous mode (selectable by sending target information followed by the start command, or just sending the

start command), the vehicle will continue with its task if the communication breaks down. In manual mode (if the stop command was send, or after switching the vehicle on), the vehicle will stop immediately after not having received any command for more than 50ms.

E-Stop is available in every mode immediately after powering the vehicle. A wireless device can be registered as e-stop device before starting the vehicle. This device can apply the start, pause and e-stop command just like the control station, but the connection to this device will be checked every 50ms. If the connection breaks, E15 will change immediately to e-stop condition.

In minimum configuration, only a small device such as a cellphone with WLAN functionality and a special android app are needed to start and operate the vehicle including the e-stop functionality.

Ready to use estop devices paired with the car will be provided.

The result data will be stored on a USB drive attached to the vehicle. They will also be sent to the control station at the end of the competition, and can be viewed on a website if the vehicle is in range of the control station or every other WLAN device connected to the vehicle.

## 3.3 Localization

E15 uses four independent GPS receivers mounted on the roof of the vehicle. This data is merged by using the number of satellites each receiver is receiving and the estimated reliability of each sensor, which is calculated according to the correctness previous data. The result of this calculation is merged with the data of a 10 DOF inertial measuring unit (three axis acceleration, three axis turn rate, three axis magnetometer and air pressure), the speed of each wheel, the angle of the steering, the data of four cameras pointing to the ground and the data from several ultrasonic sensors to determine the correct position, movement vector and speed of the vehicle.

The four GPS receivers are EM-406A SIFT III 20channel GPS Receivers, sending the position with an accuracy of about 10m.

The IMU consists of an ADXL345 accelerometer, combined with an IMU3000 turn rate sensor, a triple-axis magnetometer HMC5883L and a Bosch BMP085 air pressure sensor.

Wheel speed measurement is done using the original wheel speed sensors of a Ford Explorer, the steering angle is measured by the steering ECU (a Bosch electrical power steering).

As previously mentioned, there are also four cameras pointing to the ground. An optical flow analysis of each this cameras also gives information about the speed and direction of the vehicle. Two white markers on visible parts of the car in the field of view of each camera give the camera software information about the reliability of this measurement and the reliability of the processed images.

Also, if the vehicle is close enough to an object to see it using the ultrasonic sensors with a maximum range of about 4m. This information is also used to determine the direction and speed of the vehicle.

All this data is collected and merged by the mapping server using the reliabilities of each sensor. Further information about the sensor fusion is provided in the sensing-chapter.

There is no external map used. The car draws a map while moving, using the obstacle sensors and the target information. The map consists of tiles of 0.5*0.5m. Each tile has a counter. In the beginning, each tile is marked as “unknown” represented by 0. While driving towards the target, tiles will be

modified to “drivable” (represented by positive values) or “not passable” (represented by negative evalues). Each time an obstacle is recognized, E15 will decrease the value of the corresponding tile by a specific number. If the value of a tile is not 0, it cannot reach 0 again, this means the value will jump from -1 to 1 and from 1 to -1. If no obstacle is spotted, the value of the corresponding tile will be increased by a specific value.

Then, A* is applied ten times each second to this map to find a path to the target area.

## 3.4 Sensing

E15 senses obstacles in its environment using three Radar sensors, one Lidar sensor , thirty ultrasonic sensors and a camera system based on sixteen 13MP cameras and five 3MP infrared cameras.

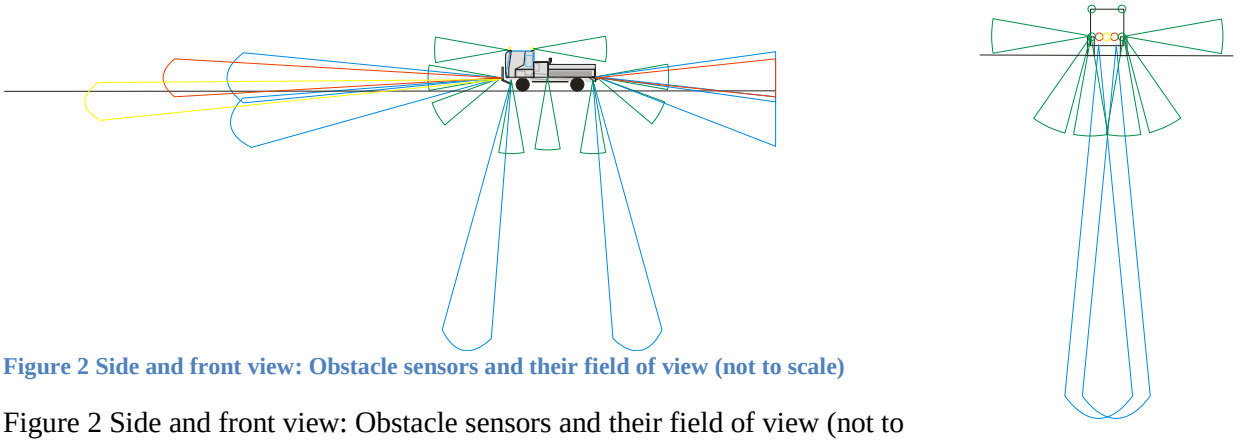

**Figure 2 Side and front view: Obstacle sensors and their field of view (not to scale)**

Figure 2 Side and front view: Obstacle sensors and their field of view (not to scale) shows the fields of view of the obstacle sensors. Ultrasonic sensors are shown in green, the vision system is colored blue, radar sensors are shown in red and the lidar sensor is tagged yellow. These sensors are also used for ground recognition and speed calculation.

The fields of view of the sensors are orientet the way that there are at least three sensors of different type have the same field of view, but with different ranges. An obstacle will first be recognized by the long range radar in a distance of about 300m , then by the lidar and the radar in a distance of about 250m, and then by the lidar, the radar and the camera system in a distance of about 200m. If the obstacle gets very close, it is also recognized by the ultrasonic sensors. The ultrasonic sensors are usually only used for navigation in underground structures, for ground recognition and the docking algorithm in the charging station. Each of these sensors calculates the positions of the obstacles using its own position and field of view relative to the vehicle, and reports a vector to the obstacle and the movement vector of the obstacle to the path planning server. This server also does the sensor fusion using the Dempster-Shafer method and draws the map of the environment. The necessary reliability of the sensors is based on empirically determined start values, modified by sensors and algorithms that measure the reliability of the other sensors.

Therefore, there is special optical sensor on the roof, based on a simple IR LED and an LDR in tubes pointing to each other. This device is able to measure the reliability of light based sensors. If the light of the LED doesn’t reach the LDR on the other side of the roof, there is for example a lot of smoke or rain, and the values received by the camera system and the lidar will be evaluated only for testing purpose, but will not be used in navigation and obstacle avoidance. Beside this optical sensor, there

two ultrasonic sensors mounted at the front and the rear of the car, pointing to the car itself. If this part of the car gets muddy, and the ultrasonic sensors will then send false values for the (known) distance, the other ultrasonic sensors in this area will be computed with decreased reliability values. The radar sensors already transmit reliability values for each obstacle.

The maximum speed of E15 is calculated using the reliability of the sensors, the minimum distance to the obstacles in direction of movement and to the sides and the steering angle.

The road, or at least the drivable area is recognized by the camera system, the lidar sensor and the ultrasonic sensors. The server checks if there is an obstacle directly in front of the vehicle, using the data of the lidar sensor, radar sensors and the ultrasonic sensors. If there is no obstacle, this “free” area is transmitted to the camera system then uses the structure and the color of this area to search for similar areas in the picture, and sends them as drivable area to the path planning server, which also combines them with the data received from the other sensors.

The vehicle speed measurement and the reliability control for the used cameras is described under “Localization”.

### 3.4.1 Sensors in detail

#### *3.4.1.1 Radar*

The three radar sensors are Bosch LRR3 Long range radar sensors, which are designed for use in the front bumper of cars. They are prepares for rough conditions, they are very fast, not sensitive to water and dust, have a built in rain recognition and they already have a heating device to remove ice from the sensor.

#### *3.4.1.2 Lidar*

The lidar sensor at the front is an Ibeo Alasca XT, mounted in a water- and dustproof case. The sensor has a built in rain recognition, and also recognizes the ground by itself. This means, that nick movements such as accelerating, breaking and driving in rough terrain will not irritate the sensor. The front window of the sensor is kept clean by using compressed air. The lidar sensor and its compressed air cleaning device on top of the waterproof housing are shown in Figure 3 Lidar it and its sensor cleaning device

**Figure 3 Lidar it and its sensor cleaning device**

#### *3.4.1.3 Ultrasonic sensors*

The Ultrasonic sensors are simple HC-SR4 sensors, but with waterproof receivers and transmitters. Each sensor got a simple 8-Bit microcontroller which reads the sensor values and transmits them to the path planning server. These sensors were used because of availability.

**Figure 4Ultrasonic sensors for ground- and obstacle recognition**

#### 3.4.1.4 Camera system

The camera system is based on 16 day vision cameras and 5 night vision cameras. The day vision cameras have a resolution of 13MP and are connected to the corresponding server directly via USB 2.0. The cameras are used, because they are also part of several lectures at the university, so the whole team has a lot of experience in image processing using these cameras, and knows exactly the strengths and weaknesses of these cameras. The night vision cameras are attached to the server using and LVDS interface, and have a resolution of 5MP each.

**Figure 5 Camera system and radar sensor without the waterproof housing**

They are used if the brightness of the images received by the day vision system gets to low, but the optical sensor on the roof doesn't indicate any smoke, dust or similar problems. The reliability of the cameras is checked by using white markers in the field of view of each camera, and the vision sensor on the roof of the vehicle. The camera system is used for completely autonomous mode, but also takes pictures of recognized POIs for further evaluation. Only the cameras in the driving direction and to the sides of the vehicle will be evaluated for obstacle recognition.

#### 3.4.1.5 Gas sensors

E15 is also equipped with several gas indication sensors. These sensors simply report the presence of a group of gasses, without naming them exactly. They also can't determine the exact concentration of the gasses. The values of these sensors are stored in the map. Receiving information about the presence of specific gasses, which can be defined via the web interface, leads to an acoustic warning.

#### 3.4.1.6 Temperature and humidity sensors

Six Sensirion SHT71 sensors are mounted at the vehicle, measuring humidity and temperature. This data is also stored in the map combined with a timestamp. These sensors are used because the team already had experience with those sensors. They were already used in several reliability experiments.

## 3.5 Vehicle control

The vehicle is completely autonomous, and just needs to get target information and a special task, which can be specified using a web interface, the control station or a monitor attached to the vehicle.

Implemented scenarios are waypoint following including the autonomous navigation from one waypoint to the other without a given map, autonomous mapping of an unknown area with and without the availability of GPS including autonomous return to the starting point after a specific time, autonomous search for a specific object like a blue container including loading it autonomously, autonomous transportation between two waypoints like the autonomous evacuation of underground areas.

If a specific time of return is given , the vehicle will always calculate the time needed to return to the starting point, and will return in time to transmit the collected data autonomously.

If the vehicle is in range of the control station, the target information such as waypoints or mode of operation can be changed at all time. In this case, the vehicle can also be controlled manually using the control station. Therefore, the control station is equipped with two joysticks, one for the control of the vehicle using live data from all the sensors, and the other one for the control of the picker arms. If the communication gets lost while operating manually, E15 will continue autonomously. There's also the

possibility to define other tasks for this case, such as return to starting point or move back 2m or more difficult operations.

The car can drive in both directions, forward and reverse, and will change direction automatically while maneuvering in narrow roads, underground structures and while navigating through sharp turns. Speed in reverse is limited to 8km/h because of the missing lidar sensor and one missing radar sensor on the rear.

## 3.6 System readiness

At this point, the powertrain and steering of the vehicle are fully functional. The vehicle is driving and all the sensors are working, but the image recognition of POI needs to be tested under rough conditions containing mud and dust. Sensor fusion and mapping are working and being tested at the moment. The picker arms are fully functional and ready for the competition, but the big picker arm still needs to be mounted on the vehicle. The maximum vehicle speed is reduced to 10km/h for save testing at the moment, but will be increased soon to the maximum of 37 km/h. First test in an underground workshop and on a grass airfield where already done, the vehicle is now back at the workshop and was modified to get the sensors on the rear bumper more mud resistant. Tests on large gravel areas, gravel roads, mud roads, a firefighting training ground including smoke filled buildings and narrow roads and a test track through the mountains will be finished by the end of July.

First tests such as forced sensor failure while driving, communication loss, moving obstacles, bright light sources in front of the camera, fog and smoke in front of each sensor, mechanical shock, forced failure of one of the brake systems (hydraulic brake, park brake or elektronic brake) demonstrated the stability and robustness of the system.

Before the competition, the influence of mud and water to the camera vision system must be reduced. Therefore, this system will be protected with a compressed air wiper system which is already used to protect the lidar sensor.

The testing has to be continued, the Android app for remote control and estop has to be finished, the control station has to be finished and the sensor fusion algorithm has to be adjusted. Also, the camera system will get more functionality like automated reading of ERIcards, the warning lights, the optical sensor on the roof, the antennas and the gas sensors have to be mounted.

At the moment, the mounting points for the camera vision system and the ultrasonic sensors are reworked to be less sensitive to vibrations and mud, to support the camera system, there will be 6 LED headlights mounted on the roof of the vehicle. These headlights are commercial headlights used in the mini.

The technology readiness level of the hardware is level 7. The testing under the expected conditions has started, and there will be no big changes except the improvement of sensor mounts, the sensor protection system and some case parts with only optical purpose.

The technology readiness level of software is also level7. The relevant parts of the software are implemented and ready for testing under the expected conditions. Testing has started, some modifications will be applied depending on the results of the following tests. Only uncritical parts of

the software, like POI evaluation and further functionality like an Android app for remote control are missing.

## 4.0 Scenario specific features

E15 is equipped with two picker arms in the middle of the car, reaching about 1m around the contours of the vehicle. These pickers can handle about 30kg, however they are not able to reach the ground. They are designed to reach the loading area of a pickup or a valve of a railway car. These picker arms can be equipped with different grippers. The grippers mounted in Figure 1 E15 without batteries and generator in the workshop (Title) are able to turn ball valves and the valves used at railway cars by turning the gripper itself. This operation can be performed autonomously if the color and type of the valve is known by using the camera system for valve detection, semi autonomously by selecting the valve on an image transmitted to the operator, or manually by manually controlling.

The manipulation software is not dependent on flat ground. In autonomous and semi-autonomous mode, the arm movement is completely controlled by the vision system on the sides of the vehicle.

E15 is able to climb obstacles with a height of at least 22cm, this also includes wet, slippery railroad tracks.

High speeds at up to 25km/h in autonomous mode in rough terrain, and 37km/h in flat terrain enable the vehicle to approach the place of action very fast.

All sensor information, including the map, the gas sensors and the images from the camera will be passed to the operator, if the control station is in range. Also, this sensor data can be viewed using WLAN and an Android app.

If the gas sensors detect explosive gases, the motor will be turned off immediately, and brakes will be applied. Servers and sensors will keep running. An acoustic and optical warning signal will be started. This can be deactivated using the control station or the Android app. E15 will then continue working at its given task. This feature can be deactivated at the vehicle itself before transmitting a task.

The localization also works without GPS by only using the IMU, the distance to obstacles, the wheel speed measurement and the camera system, if available. GPS will be ignored if there is no reception for example while navigating between huge buildings or railroad cars or under metal roofs like on train stations.

If the control station is in range, the map and live sensor data will be sent to the control station using WLAN. POIs will also be available in this map. This data is also available using the web interface. However, there will be nearly no possibility to communicate with the vehicle after it entered the underground structure. The vehicle will get a return time at the beginning and calculate the time it needs to drive back to the starting point. It will autonomously return to the starting point if half of the remaining time is needed for a save return. This path will be calculated using A* and the map. After returning into the range of the control station, data will be transmitted autonomously.

The map will be available as a scaled image containing a legend, a text file containing exact positions of waypoints and POIs.

As already described in “sensors”, the sensors are protected against mud and dust using a compressed air system. Smoke and dust will lead to the deactivation of the camera system and the lidar sensor, and reduce the maximum speed of the vehicle. In case of darkness, the vehicle will switch from the day vision cameras to the night vision cameras, reduce the driving speed and turn on the six LED headlights.

E15 can handle high humidity without any problems. The sensors are protected against condensing water, and the electronic box and all parts at high voltage are heated or protected against condensing water by humidity traps (both based on peltier elements) if the SHT71 humidity sensors recognize high values of humidity and a temperature close to the dewpoint or below it.

As already described, communication to the vehicle is only necessary at the beginning and the end of the scenario, while the vehicle is in range of the control station. If the communication gets lost, the vehicle will continue with its task. However, communication with the paired e-stop device is necessary for this task. Loss of the communication to the e-stop device will lead to immediate e-stop.

## 5.0 Table of figures

Hochschule Esslingen
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# Team E15 - Mobile manipulation for handling hazardous material

*Scenario Application Paper*

**Figure 1 E15 without batteries and generator in the workshop**

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## 1.0 Abstract

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The sensors are organized in clusters, containing sensors of the same type near the same position. Those clusters have the same cluster controller, which reads and collects the sensor data. This controller provides also information about the position of the sensors. The data is transmitted to the server using CAN (ISO 11898).

In case of the ultrasonic sensors, the gas sensors and the other sensors with low complexity, the cluster controller is an STM32F407, while the computer vision system, the LIDAR sensors and the radar sensor have two own industrial computer system.

The server for sensor fusion and mapping is an i7-3610QE on an Advantech AIMB-273 mainboard with 8GB ram and a compact fast drive with 16GB. This server communicates with the cluster controllers using CAN, if they are microcontroller based, and with the computer based cluster controllers using a redundant LAN connection, the motor controller, robot arms and the steering are connected to the server using a separate CAN.

This structure allows big distances between the different sensors and the server.

Image processing is done on several commercial industrial PCs using C++ and openCV. The obstacle and road data is transmitted to the server via sockets using vectors. All the computers are running RTOS in the competition, but there are also experiments with Arch Linux just for testing.

The target data and other relevant data such as mission information, mode of operation and waypoint data can be submitted using a simple PHP form, using the onboard computer system or connecting to a socket using the W-LAN connection.

## 3.2 Communication

The vehicle is operated completely autonomous, so the communication to a specific control station is only needed to start the vehicle at the beginning of the competition and get the collected data at the end of the competition. If the vehicle is in range, it can be controlled manually by an operator.

E15 and the control station are both equipped with a standard WLAN AP (Hirschmann BAT 54 F, IEEE 802.11a/b/g/h/i ), which is connected to a redundant LAN switch(). Every single connection is redundant (PRP). Two independent wireless channels, two CAT6 cables, two LAN interfaces on each device. Switch and AP are certified according to EN 61000-6-2, EN 61131 for use in automation anvironment; E1 certification for use in vehicles; EN50155 for use in trains and are tested for salt spray according to DIN EN 60068-2-52.

The car usually just listens for start, pause or stop commands or target information. In autonomous mode (selectable by sending target information followed by the start command, or just sending the

start command), the vehicle will continue with its task if the communication breaks down. In manual mode (if the stop command was send, or after switching the vehicle on), the vehicle will stop immediately after not having received any command for more than 50ms.

E-Stop is available in every mode immediately after powering the vehicle. A wireless device can be registered as e-stop device before starting the vehicle. This device can apply the start, pause and e-stop command just like the control station, but the connection to this device will be checked every 50ms. If the connection breaks, E15 will change immediately to e-stop condition.

In minimum configuration, only a small device such as a cellphone with WLAN functionality and a special android app are needed to start and operate the vehicle including the e-stop functionality.

Ready to use estop devices paired with the car will be provided.

The result data will be stored on a USB drive attached to the vehicle. They will also be sent to the control station at the end of the competition, and can be viewed on a website if the vehicle is in range of the control station or every other WLAN device connected to the vehicle.

## 3.3 Localization

E15 uses four independent GPS receivers mounted on the roof of the vehicle. This data is merged by using the number of satellites each receiver is receiving and the estimated reliability of each sensor, which is calculated according to the correctness previous data. The result of this calculation is merged with the data of a 10 DOF inertial measuring unit (three axis acceleration, three axis turn rate, three axis magnetometer and air pressure), the speed of each wheel, the angle of the steering, the data of four cameras pointing to the ground and the data from several ultrasonic sensors to determine the correct position, movement vector and speed of the vehicle.

The four GPS receivers are EM-406A SIFT III 20channel GPS Receivers, sending the position with an accuracy of about 10m.

The IMU consists of an ADXL345 accelerometer, combined with an IMU3000 turn rate sensor, a triple-axis magnetometer HMC5883L and a Bosch BMP085 air pressure sensor.

Wheel speed measurement is done using the original wheel speed sensors of a Ford Explorer, the steering angle is measured by the steering ECU (a Bosch electrical power steering).

As previously mentioned, there are also four cameras pointing to the ground. An optical flow analysis of each this cameras also gives information about the speed and direction of the vehicle. Two white markers on visible parts of the car in the field of view of each camera give the camera software information about the reliability of this measurement and the reliability of the processed images.

Also, if the vehicle is close enough to an object to see it using the ultrasonic sensors with a maximum range of about 4m. This information is also used to determine the direction and speed of the vehicle.

All this data is collected and merged by the mapping server using the reliabilities of each sensor. Further information about the sensor fusion is provided in the sensing-chapter.

There is no external map used. The car draws a map while moving, using the obstacle sensors and the target information. The map consists of tiles of 0.5*0.5m. Each tile has a counter. In the beginning, each tile is marked as “unknown” represented by 0. While driving towards the target, tiles will be

modified to “drivable” (represented by positive values) or “not passable” (represented by negative evalues). Each time an obstacle is recognized, E15 will decrease the value of the corresponding tile by a specific number. If the value of a tile is not 0, it cannot reach 0 again, this means the value will jump from -1 to 1 and from 1 to -1. If no obstacle is spotted, the value of the corresponding tile will be increased by a specific value.

Then, A* is applied ten times each second to this map to find a path to the target area.

## 3.4 Sensing

E15 senses obstacles in its environment using three Radar sensors, one Lidar sensor , thirty ultrasonic sensors and a camera system based on sixteen 13MP cameras and five 3MP infrared cameras.

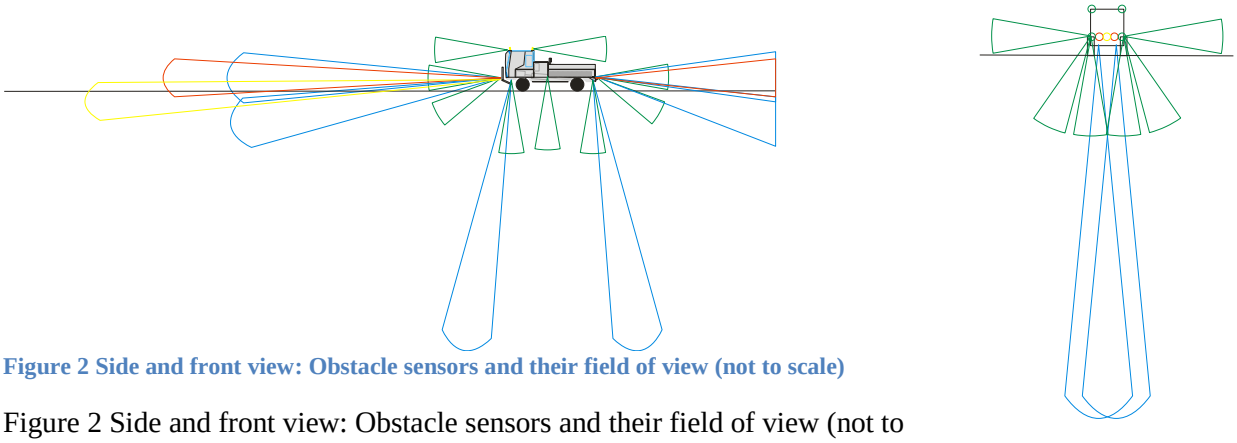

**Figure 2 Side and front view: Obstacle sensors and their field of view (not to scale)**

Figure 2 Side and front view: Obstacle sensors and their field of view (not to scale) shows the fields of view of the obstacle sensors. Ultrasonic sensors are shown in green, the vision system is colored blue, radar sensors are shown in red and the lidar sensor is tagged yellow. These sensors are also used for ground recognition and speed calculation.

The fields of view of the sensors are orientet the way that there are at least three sensors of different type have the same field of view, but with different ranges. An obstacle will first be recognized by the long range radar in a distance of about 300m , then by the lidar and the radar in a distance of about 250m, and then by the lidar, the radar and the camera system in a distance of about 200m. If the obstacle gets very close, it is also recognized by the ultrasonic sensors. The ultrasonic sensors are usually only used for navigation in underground structures, for ground recognition and the docking algorithm in the charging station. Each of these sensors calculates the positions of the obstacles using its own position and field of view relative to the vehicle, and reports a vector to the obstacle and the movement vector of the obstacle to the path planning server. This server also does the sensor fusion using the Dempster-Shafer method and draws the map of the environment. The necessary reliability of the sensors is based on empirically determined start values, modified by sensors and algorithms that measure the reliability of the other sensors.

Therefore, there is special optical sensor on the roof, based on a simple IR LED and an LDR in tubes pointing to each other. This device is able to measure the reliability of light based sensors. If the light of the LED doesn’t reach the LDR on the other side of the roof, there is for example a lot of smoke or rain, and the values received by the camera system and the lidar will be evaluated only for testing purpose, but will not be used in navigation and obstacle avoidance. Beside this optical sensor, there

two ultrasonic sensors mounted at the front and the rear of the car, pointing to the car itself. If this part of the car gets muddy, and the ultrasonic sensors will then send false values for the (known) distance, the other ultrasonic sensors in this area will be computed with decreased reliability values. The radar sensors already transmit reliability values for each obstacle.

The maximum speed of E15 is calculated using the reliability of the sensors, the minimum distance to the obstacles in direction of movement and to the sides and the steering angle.

The road, or at least the drivable area is recognized by the camera system, the lidar sensor and the ultrasonic sensors. The server checks if there is an obstacle directly in front of the vehicle, using the data of the lidar sensor, radar sensors and the ultrasonic sensors. If there is no obstacle, this “free” area is transmitted to the camera system then uses the structure and the color of this area to search for similar areas in the picture, and sends them as drivable area to the path planning server, which also combines them with the data received from the other sensors.

The vehicle speed measurement and the reliability control for the used cameras is described under “Localization”.

### 3.4.1 Sensors in detail

#### *3.4.1.1 Radar*

The three radar sensors are Bosch LRR3 Long range radar sensors, which are designed for use in the front bumper of cars. They are prepares for rough conditions, they are very fast, not sensitive to water and dust, have a built in rain recognition and they already have a heating device to remove ice from the sensor.

#### *3.4.1.2 Lidar*

The lidar sensor at the front is an Ibeo Alasca XT, mounted in a water- and dustproof case. The sensor has a built in rain recognition, and also recognizes the ground by itself. This means, that nick movements such as accelerating, breaking and driving in rough terrain will not irritate the sensor. The front window of the sensor is kept clean by using compressed air. The lidar sensor and its compressed air cleaning device on top of the waterproof housing are shown in Figure 3 Lidar it and its sensor cleaning device

**Figure 3 Lidar it and its sensor cleaning device**

#### *3.4.1.3 Ultrasonic sensors*

The Ultrasonic sensors are simple HC-SR4 sensors, but with waterproof receivers and transmitters. Each sensor got a simple 8-Bit microcontroller which reads the sensor values and transmits them to the path planning server. These sensors were used because of availability.

**Figure 4Ultrasonic sensors for ground- and obstacle recognition**

#### 3.4.1.4 Camera system

The camera system is based on 16 day vision cameras and 5 night vision cameras. The day vision cameras have a resolution of 13MP and are connected to the corresponding server directly via USB 2.0. The cameras are used, because they are also part of several lectures at the university, so the whole team has a lot of experience in image processing using these cameras, and knows exactly the strengths and weaknesses of these cameras. The night vision cameras are attached to the server using and LVDS interface, and have a resolution of 5MP each.

**Figure 5 Camera system and radar sensor without the waterproof housing**

They are used if the brightness of the images received by the day vision system gets to low, but the optical sensor on the roof doesn't indicate any smoke, dust or similar problems. The reliability of the cameras is checked by using white markers in the field of view of each camera, and the vision sensor on the roof of the vehicle. The camera system is used for completely autonomous mode, but also takes pictures of recognized POIs for further evaluation. Only the cameras in the driving direction and to the sides of the vehicle will be evaluated for obstacle recognition.

#### 3.4.1.5 Gas sensors

E15 is also equipped with several gas indication sensors. These sensors simply report the presence of a group of gasses, without naming them exactly. They also can't determine the exact concentration of the gasses. The values of these sensors are stored in the map. Receiving information about the presence of specific gasses, which can be defined via the web interface, leads to an acoustic warning.

#### 3.4.1.6 Temperature and humidity sensors

Six Sensirion SHT71 sensors are mounted at the vehicle, measuring humidity and temperature. This data is also stored in the map combined with a timestamp. These sensors are used because the team already had experience with those sensors. They were already used in several reliability experiments.

## 3.5 Vehicle control

The vehicle is completely autonomous, and just needs to get target information and a special task, which can be specified using a web interface, the control station or a monitor attached to the vehicle.

Implemented scenarios are waypoint following including the autonomous navigation from one waypoint to the other without a given map, autonomous mapping of an unknown area with and without the availability of GPS including autonomous return to the starting point after a specific time, autonomous search for a specific object like a blue container including loading it autonomously, autonomous transportation between two waypoints like the autonomous evacuation of underground areas.

If a specific time of return is given , the vehicle will always calculate the time needed to return to the starting point, and will return in time to transmit the collected data autonomously.

If the vehicle is in range of the control station, the target information such as waypoints or mode of operation can be changed at all time. In this case, the vehicle can also be controlled manually using the control station. Therefore, the control station is equipped with two joysticks, one for the control of the vehicle using live data from all the sensors, and the other one for the control of the picker arms. If the communication gets lost while operating manually, E15 will continue autonomously. There's also the

possibility to define other tasks for this case, such as return to starting point or move back 2m or more difficult operations.

The car can drive in both directions, forward and reverse, and will change direction automatically while maneuvering in narrow roads, underground structures and while navigating through sharp turns. Speed in reverse is limited to 8km/h because of the missing lidar sensor and one missing radar sensor on the rear.

## 3.6 System readiness

At this point, the powertrain and steering of the vehicle are fully functional. The vehicle is driving and all the sensors are working, but the image recognition of POI needs to be tested under rough conditions containing mud and dust. Sensor fusion and mapping are working and being tested at the moment. The picker arms are fully functional and ready for the competition, but the big picker arm still needs to be mounted on the vehicle. The maximum vehicle speed is reduced to 10km/h for save testing at the moment, but will be increased soon to the maximum of 37 km/h. First test in an underground workshop and on a grass airfield where already done, the vehicle is now back at the workshop and was modified to get the sensors on the rear bumper more mud resistant. Tests on large gravel areas, gravel roads, mud roads, a firefighting training ground including smoke filled buildings and narrow roads and a test track through the mountains will be finished by the end of July.

First tests such as forced sensor failure while driving, communication loss, moving obstacles, bright light sources in front of the camera, fog and smoke in front of each sensor, mechanical shock, forced failure of one of the brake systems (hydraulic brake, park brake or elektronic brake) demonstrated the stability and robustness of the system.

Before the competition, the influence of mud and water to the camera vision system must be reduced. Therefore, this system will be protected with a compressed air wiper system which is already used to protect the lidar sensor.

The testing has to be continued, the Android app for remote control and estop has to be finished, the control station has to be finished and the sensor fusion algorithm has to be adjusted. Also, the camera system will get more functionality like automated reading of ERIcards, the warning lights, the optical sensor on the roof, the antennas and the gas sensors have to be mounted.

At the moment, the mounting points for the camera vision system and the ultrasonic sensors are reworked to be less sensitive to vibrations and mud, to support the camera system, there will be 6 LED headlights mounted on the roof of the vehicle. These headlights are commercial headlights used in the mini.

The technology readiness level of the hardware is level 7. The testing under the expected conditions has started, and there will be no big changes except the improvement of sensor mounts, the sensor protection system and some case parts with only optical purpose.

The technology readiness level of software is also level7. The relevant parts of the software are implemented and ready for testing under the expected conditions. Testing has started, some modifications will be applied depending on the results of the following tests. Only uncritical parts of

the software, like POI evaluation and further functionality like an Android app for remote control are missing.

## 4.0 Scenario specific features

E15 is equipped with two picker arms in the middle of the car, reaching about 1m around the contours of the vehicle. These pickers can handle about 30kg, however they are not able to reach the ground. They are designed to reach the loading area of a pickup or a valve of a railway car. These picker arms can be equipped with different grippers. The grippers mounted in Figure 1 E15 without batteries and generator in the workshop (Title) are able to turn ball valves and the valves used at railway cars by turning the gripper itself. This operation can be performed autonomously if the color and type of the valve is known by using the camera system for valve detection, semi autonomously by selecting the valve on an image transmitted to the operator, or manually by manually controlling.

The manipulation software is not dependent on flat ground. In autonomous and semi-autonomous mode, the arm movement is completely controlled by the vision system on the sides of the vehicle.

E15 is able to climb obstacles with a height of at least 22cm, this also includes wet, slippery railroad tracks.

High speeds at up to 25km/h in autonomous mode in rough terrain, and 37km/h in flat terrain enable the vehicle to approach the place of action very fast.

All sensor information, including the map, the gas sensors and the images from the camera will be passed to the operator, if the control station is in range. Also, this sensor data can be viewed using WLAN and an Android app.

If the gas sensors detect explosive gases, the motor will be turned off immediately, and brakes will be applied. Servers and sensors will keep running. An acoustic and optical warning signal will be started. This can be deactivated using the control station or the Android app. E15 will then continue working at its given task. This feature can be deactivated at the vehicle itself before transmitting a task.

The localization also works without GPS by only using the IMU, the distance to obstacles, the wheel speed measurement and the camera system, if available. GPS will be ignored if there is no reception for example while navigating between huge buildings or railroad cars or under metal roofs like on train stations.

If the control station is in range, the map and live sensor data will be sent to the control station using WLAN. POIs will also be available in this map. This data is also available using the web interface. However, there will be nearly no possibility to communicate with the vehicle after it entered the underground structure. The vehicle will get a return time at the beginning and calculate the time it needs to drive back to the starting point. It will autonomously return to the starting point if half of the remaining time is needed for a save return. This path will be calculated using A* and the map. After returning into the range of the control station, data will be transmitted autonomously.

The map will be available as a scaled image containing a legend, a text file containing exact positions of waypoints and POIs.

As already described in “sensors”, the sensors are protected against mud and dust using a compressed air system. Smoke and dust will lead to the deactivation of the camera system and the lidar sensor, and reduce the maximum speed of the vehicle. In case of darkness, the vehicle will switch from the day vision cameras to the night vision cameras, reduce the driving speed and turn on the six LED headlights.

E15 can handle high humidity without any problems. The sensors are protected against condensing water, and the electronic box and all parts at high voltage are heated or protected against condensing water by humidity traps (both based on peltier elements) if the SHT71 humidity sensors recognize high values of humidity and a temperature close to the dewpoint or below it.

As already described, communication to the vehicle is only necessary at the beginning and the end of the scenario, while the vehicle is in range of the control station. If the communication gets lost, the vehicle will continue with its task. However, communication with the paired e-stop device is necessary for this task. Loss of the communication to the e-stop device will lead to immediate e-stop.

## 5.0 Table of figures