TrimBot2020 Deliverable D6.2

System integration for demonstrator 1

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Abstract: Demonstrator 1 is the mobile platform with integrated software system needed for the first Trimbot demonstration in September 2017. The demonstration is about the navigation in a test garden. Thus, all the software components needed for navigation have to be integrated in this demonstrator. This document describes the integration of the necessary components for the navigation demonstration and documents the individual integration workshops.

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1 Introduction

Demonstrator 1 is the vehicle of platform 2 with integrated software system needed for the first Trimbot demonstration in September 2017. The purpose of this demonstration is to show the vehicle's navigation capabilities using the visual SLAM localization, the interface GardenUI and the navigation software. At the project meeting in Amsterdam (18.-19. May, 2017), it was decided to integrate only the software components that are necessary for the navigation demonstration and show the other software components as standalone tools. Thus, the software integration for demonstrator 1 includes the packages for Camera (ETHZ), Semantic SLAM (ETHZ), SketchMap (UEDIN) and Navigation (BOSCH). Each of these packages consists of one or more components which have to be integrated into an overall system. An overview of the software integration for demonstrator 1 follows in Section 3. The hardware integration for demonstrator 1 was mainly the integration of the cameras into the vehicle and the setup of the network infrastructure which allows an easy integration of additional PCs or Laptops. In the case of the navigation demonstration, this is the SLAM laptop of ETHZ. The integration process of the hardware is documented in Section 2. A detailed description of the hardware itself can be found in Deliverable 1.2 (Platform 2: Supports online operation for demonstrator 1).

In order to prepare platform 2 for the demonstration and to integrate all independently implemented and tested components into an overall system, several integration workshops were carried out. An overview of these workshops is given in Table 1. A detailed documentation of these workshops and the obtained results are described in Section 4.

Month	Date	Description		Participant
15	03 / 17	Vehicle + Camera Integration	Workshop	Bosch, ETHZ
17	05 / 17	All components implemented as ROS nodes and individually tested	Software Deliverable	Bosch, UEDIN, ETHZ
18	06 / 17	UI + Robot Integration	Workshop	Bosch, UEDIN
19	07 / 17	SLAM Integration 1	Workshop	Bosch, UEDIN, ETHZ
20	08 / 17	SLAM Integration 2	Workshop	Bosch, UEDIN, ETHZ
21	09 / 17	SLAM Integration 3	Workshop	Bosch, UEDIN, ETHZ
21	09 / 17	System Integration	Workshop	Bosch, UEDIN, ETHZ

Table 1: Integration timeline and workshops for demonstrator 1.

2 Hardware Integration

The hardware integration included the mobile platform provided by Bosch and the vehicle cameras provided by ETHZ. Several iterations were needed to find the final camera configuration. The final decision was made for a pentagon camera arrangement with five stereo camera pairs. Each pair consisting of a grey value camera and a colour camera with a baseline of 3.0 cm and s-mount lenses with a focal length of 500 pixels. After the final decision was made a camera housing was built by WR. During the camera integration workshop the five stereo camera pairs were mounted into the housing and then the housing to the vehicle. Also a calibration of the cameras was carried out during this workshop. The camera setup, camera calibration and stereo processing on the FPGA of the cameras is described in more detail in D1.2, D3.1 and D3.2. More details about the camera integration workshop are given in Section4.1.

In order to be able to integrate computers from other partners, e.g. the SLAM laptop from ETHZ, a network router has been installed on the vehicle. This router also provides a wireless network to enable remote access to the vehicle for the GardenUI, and also gives remote access to the laptops on the vehicle. There is also a dedicated space on the vehicle for mounting further laptops. For the navigation demonstration the SLAM laptop from ETHZ was mounted on this dedicated space and the cameras were connected to this laptop via USB. Figure 1 shows the vehicle used for demonstrator 1 with integrated cameras and network router. More details about the vehicle and the network infrastructure is given in Deliverable 1.2 (Platform 2: Supports online operation for demonstrator 1).

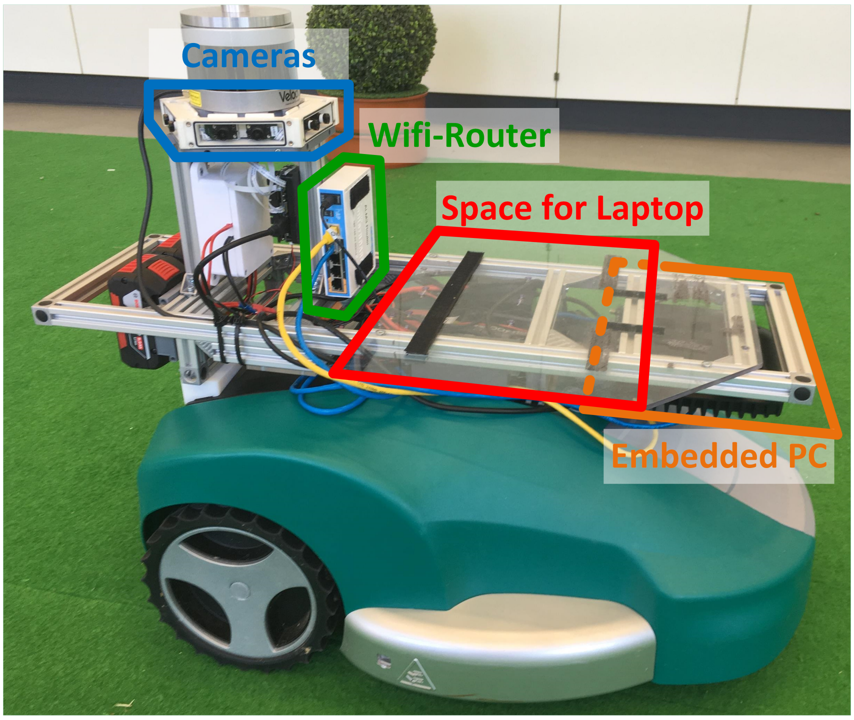


Figure 1: Demonstrator 1 with integrated cameras, Wifi-Router and additional space for the SLAM laptop from ETHZ.

3 Software Integration

The software integration for demonstrator 1 is derived from the requirements of the navigation demonstration and therefore includes the Camera (CAM) package from ETHZ, the SLAM package also from ETHZ, the SketchMap (MAP) package from UEDIN and the Navigation (NAV) package from Bosch. Figure 2 shows the overall software architecture, with all packages involved in integration for demonstrator 1 highlighted in green.

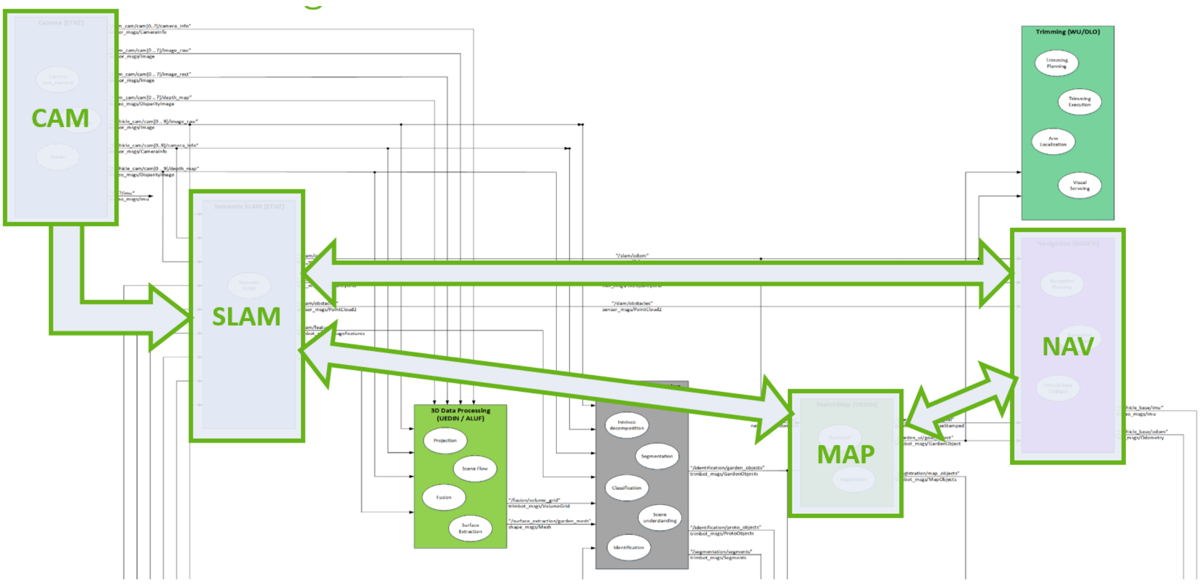


Figure 2: Overall software architecture. The packages involved in the integration for demonstrator 1 are highlighted green.

The navigation demonstration can be divided in two parts. On the one hand mapping which is done in a manual offline process and on the other hand online navigation which requires a localization in the previously created map. For software integration, this means that the data exchange between the individual components can be handled differently. It was therefore agreed that during the mapping process, the data transfer takes place through sharing of files, while in the online navigation, the data exchange takes place via ROS messages.

For the mapping the robot was driven through the garden by a remote control and a ROS bagfile for the image streams of all cameras was recorded. Based on this bagfile the SLAM offline reconstruction creates a 3D point cloud file of the garden. This 3D point cloud file is then the starting point for a manual registration in the GardenUI. After a successful registration the GardenUI is used to generate a 2D occupancy grid of the garden. This occupancy grid is stored as an image file and description file which can be loaded by the ROS map server. The map server provides then the information about free space and obstacles to the navigation software (move_base) as ROS messages during the online navigation.

The online navigation requires from the SLAM algorithm a localization of the robot in the garden w.r.t. the previously built map. This robot position is then provided to the GardenUI and the navigation software as ROS messages. If the robots current position is available the user can define a goal in the GardenUI which will then be sent to the navigation software. The navigation software then plans a drivable path to reach this goal taking into account the obstacles and free space from the occupancy grid.

As both the Camera package and the SLAM package are provided by the ETHZ no dedicated integration workshop between these two packages was needed. A first software integration workshop was accomplished for the integration of the user interface (GardenUI), master state machine and the navigation package. Further software integration workshops were organized to integrate the SLAM package to achieve an overall software system for the navigation demonstration. More details about the integration workshops is given in Section 4.

4 Integration Workshops

In addition to the integration sessions during the consortium meetings, a total of six integration workshops were necessary for the system integration of demonstrator 1. In the first integration workshop, the cameras were integrated into the vehicle and calibrated. In the second integration workshop the user interface (GardenUI) and the navigation package including the master state machine were integrated. The next step was then the integration of the SLAM components. For the integration of these components three further integration workshops were needed. In the last integration workshop all components were tested together and the navigation demonstration was prepared.

4.1 Camera Integration

Location: Robert Bosch GmbH, 71272 Renningen, Germany

Date: 28. - 29. March 2017

Participants: Dominik Honegger (ETHZ), Radim Tylecek (UEDIN), Michael Blaich (BOSCH) and Sebastian Haug (BOSCH)

In preparation for this workshop, the cameras were mounted into the 3D printed pentagonal housing and the housing with all cameras and FPGA was mounted to the vehicle. During the workshop the cameras were calibrated to estimate their intrinsic and extrinsic parameters as well as their position w.r.t. the vehicle. For the intrinsic and extrinsic parameter calibration, an A0 calibration pattern was move around the robot while the images from the cameras are recorded to a ROS bagfile. The Kalibr tool was then used to estimate the camera parameters based on the previously recorded bagfile. The result of the camera calibration is a calibration file with all camera parameters. This calibration file is then loaded by the camera driver that sets the camera parameters into the FPGA to enable the provision of rectified and depth images. Several data sets with this calibration setting were recorded to check visually if the calibrated parameters produce good results. For the estimation of the camera's position w.r.t. the vehicle an A3 calibration pattern was mounted to the vehicle. For this setup also a ROS bagfile was recorded to be able to determine the position. Some impressions from this integration workshop are shown in Figure 3.

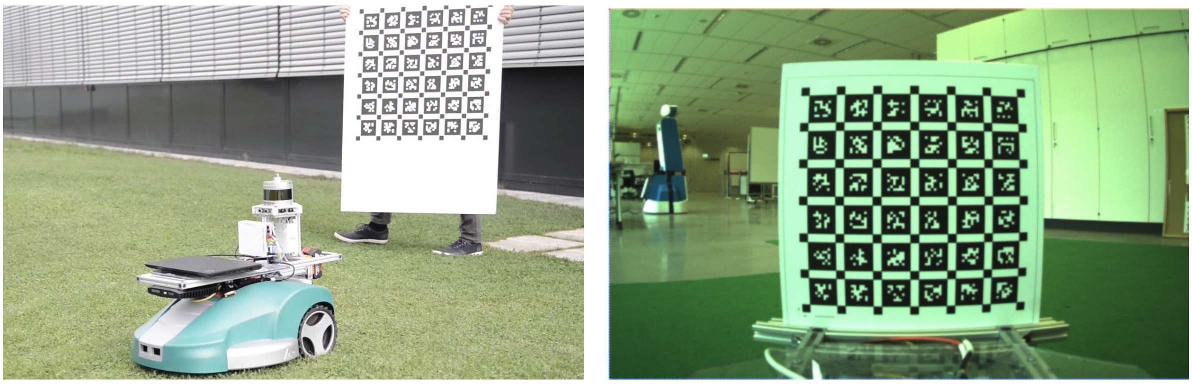


Figure 3: Impressions from the camera calibration at Bosch in Renningen.

4.2 Garden UI and Navigation Integration

Location: Robert Bosch GmbH, 71272 Renningen, Germany

Date: 7. - 8. June 2017

Participants: Radim Tylecek (UEDIN) and Michael Blaich (BOSCH)

The aim of this integration workshop was to set up the cooperation and communication between GardenUI, master state machine, navigation planning and navigation execution. Even before the workshop, all components were tested individually by both partners. During the workshop the laptop from UEDIN was integrated into the network configuration of the vehicle. The ROS communication between the embedded PC on the vehicle and the laptop was established to send commands from the GaredenUI to the master state machine and vice versa. In the first step the communication between GardenUI, master state machine and navigation planning was tested. For these purpose, every user action (simple goal, goal object, cancel goal) was sent from the GardenUI and checked whether the master state machine and navigation planning are responding accordingly. For this first tests the navigation execution was replaced by a mockup to make testing easier. After this first communication tests the navigation execution was integrated and tested indoors. Since at this time the visual SLAM from ETHZ was not yet available, a Lidar SLAM based on the Velodyne sensor was used for the localization. For the indoor test environment, with this setup, the vehicle was able to reach multiple positions and objects sent by the GardenUI as goals to the master state machine and then relayed to the navigation software. Figure 4 shows some impressions from these tests.

Figure 4: Impressions from the indoor testing during the GardenUI and navigation integration at Bosch in Renningen.

After the successful indoor tests the same setup was used to perform some outdoor tests. Figure 5 shows the vehicle and the laptop with the GardenUI during these outdoor tests. At the end of this integration workshop, the communication between the remote laptop with the GardenUI and the vehicle with all navigation components was successfully established and tested. It was now possible to define a goal in the GardenUI and send the robot to this location. After receiving a goal the master state machine triggered the navigation planning to check if the goal was reachable by the robot. If it was reachable it plans a collision free path and navigates the vehicle along this path to the location.

Figure 5: This image shows the remote laptop with the GardenUI and the vehicle during the outdoor testing of the GardenUI and navigation integration.

During the workshop the following topics were tested:

- GardenUI: Map node is running
- GardenUI: Navigation commands for simple goal (2D pose in the map is given as goal for the robot navigation), object goal (send a goal for the robot navigation based on an object selected in the GardenUI) are successful tested using Lidar localization as input for the navigation.
- GardenUI: A message to send a list of objects as successive goals was implemented but not tested because the implementation in the navigation software could not handle the list yet.
- GardenUI: Cancel command is implemented and tested
- Navigation: The master state machine is working as expected.
- Navigation: A navigation to simple goal (2D position in the map) is working but not tested with input from SLAM. A localization based on the Velodyne was used for this tests.
- Navigation: A navigation to a garden object is working but also not tested with input from SLAM. An improvement on this maneuver is also needed to reach the pose in front of the object more precisely.
- Navigation: The cancel command for a given goal is working but needs some fixes.

During the workshop, the following topics were identified as next steps.

- ◦ Navigation: Implement a behaviour in the master state machine to handle a sequence of objects sent by the GardenUI.
- ◦ Navigation: Improve the approaching of a trimming object.

4.3 SLAM Integration 1

Location: Robert Bosch GmbH, 71272 Renningen, Germany

Date: 3. - 8. July 2017

Participants: Dominik Honegger (ETHZ), Johannes Schönberger (ETHZ), Marcel Geppet (ETHZ), Radim Tylecek (UEDIN) and Michael Blaich (BOSCH)

The aim of this workshop was to create a map for the indoor test environment and localize the robot in this map to provide the robot's position to the GardenUI and the navigation software as a ROS pose and TF transform message. This should check if all interfaces between the individual components are implemented correctly.

First the robot was driven through this indoor test environment and a bagfile with the camera streams was recorded for the SLAM reconstruction. The results from the first reconstruction showed that it worked and the bushes and other obstacles are mapped in the 3D point cloud. However, it turned out that the coordinate frames between SLAM and GardenUI respectively navigation software followed not the same definition. Thus, a correction of the coordinate frames was necessary in order to obtain consistent representation of the garden and robot position. The ROS REP105[1] was defined as standard for the implementation of the coordinate frames.

The registration of the 3D point cloud file provided by the SLAM reconstruction to the GradenUI worked, however, additional manual work and transformations were needed, thus the mapping and the registration both need further improvements. As the online localization could not be tested during this workshop the navigation software was installed on the Laptop of the ETHZ to enable further tests at the ETHZ. At the end of the workshop the mapping worked in principle but needed further improvements especially for the coordinate frame. Impressions from the first SLAM integration workshop in Renningen are shown in Figure 6.

Figure 6: Impressions from the first SLAM integration workshop at Bosch in Renningen.

[1] http://www.ros.org/reps/rep-0105.html

During the workshop the following topics were tested:

- SLAM - Global 3D mapping: The reconstruction from an recorded image stream works, however, an improvement is needed for the coordinate frames and to masked out points from the robot chassis.
- GardenUI: Manual registration to the SLAM reconstruction is working but needs improvements toward a semi-automatic registration.

During the workshop, the following topics were identified as next steps.

- ◦ SLAM: Development will continue with the second Indego in Zürich. The navigation software was therefore installed on the SLAM Laptop during the workshop.
- ◦ SLAM: The generation of an occupancy grid out of the 3D point cloud has to be implemented.
- ◦ SLAM: For further testing of the SLAM algorithms the previously recorded bagfiles including ground truth positions should be used. The recordings from around_hedge_2017-03-29_15-24-07.bag and slalom_between_boxwoods_2017-03-29_13-47-48.bag were defined as test data sets.
- ◦ GardenUI: Improve the registration process towards a semi-automated registration.
- ◦ GardenUI: Overlay the objects defined in the GardenUI over the objects detected by the SLAM algorithm and merge both information into the one occupancy grid which is used for path planning and obstacle avoidance in the navigation software.

4.4 SLAM Integration 2

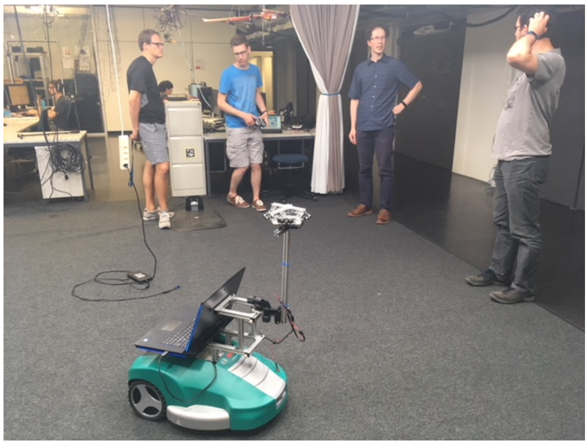
Location: ETH Zürich, 8092 Zürich, Switzerland

Date: 15. - 16. August 2017

Participants: Dominik Honegger (ETHZ), Johannes Schönberger (ETHZ), Marcel Geppet (ETHZ), Radim Tylecek (UEDIN) and Michael Blaich (BOSCH)

The aim of this workshop was to improve the navigation performance of the Indego in an indoor test scenario at the ETHZ. This was necessary to improve the interaction between SLAM localization and the navigation software. The parameters of the navigation software were optimized for the indoor test scenario by slowing down the vehicle speed and enlarging the goal tolerance for position and orientation. This was necessary because both the accuracy and the update rate of the SLAM localization had not yet reached the accuracy and update rate of the Lidar localization which was used to set up the initial parameters for the navigation software. In the course of the project, however, further improvements on the SLAM pipeline were expected, thus the robot speed can be increased again and the target tolerances can be reduced again. A second topic during the workshop was to improve the registration between the SLAM map and SketchMap from the GardenUI. Figure 7 shows some impressions from this workshop at the ETH Zürich.

(a)



(b)

Figure 7: Impressions from the second SLAM integration workshop at ETH in Zürich.

During the workshop the following topics were tested:

- SLAM: The global localization is working and the coordinate frame issues were fixed.
- SLAM/Navigation: The interaction between SLAM localization and the navigation software was tested and worked. The robot was able to reach a defined goal but with low speed and enlarged goal tolerances. A speed up of the localization is needed to reach a higher update rate of the robot position to enable a faster and more precise navigation.

During the workshop, the following topics were identified as next steps.

- SLAM: The generation of an occupancy grid out of the 3D point cloud has to be implemented.
- SLAM: Since the principal function of the SLAM localization could be shown on the indoor scenario, the next step is the localization using an outdoor data set.
- SLAM: Speed up of localization algorithm.

4.5 SLAM Integration 3

Location: Robert Bosch GmbH, 71272 Renningen, Germany

Date: 4. - 9. September 2017

Participants: Dominik Honegger (ETHZ), Johannes Schönberger (ETHZ), Marcel Geppet (ETHZ), Radim Tylecek (UEDIN) and Michael Blaich (BOSCH)

The aim of this workshop was to test the SLAM localization and the navigation software on the outdoor scenario which will be used for the navigation demonstration. First a mapping data set for the Renningen test garden was recorded. Based on this data set a SLAM map for the Renningen test garden was created. First results showed that during the mapping the blinds from the buildings around the test garden were open and the cameras looking through the windows and also mapped areas inside the buildings. However, it was expected that the blinds are closed during the demonstration, which in turn could lead to localization problems and localization may fail. Therefore, the decision was made to record a second mapping data set with closed blinds at the end of the workshop. Based on the first mapping data set two 3D point clouds from the test garden in Rennigen were created. A sparse version which was used for the localization and a dense version used for the registration in the GardenUI and the occupancy grid generation. The localization tests showed that the localization works in principle in the test garden in Renningen, however, some improvements are needed for a smooth and stable navigation. To speed up the the SLAM localization the decision was made to use the Razerblade Laptop from Bosch for the SLAM localization during the navigation demonstrations because it doesn't throttle down the GPU in battery mode. The SLAM components needed for localization were installed and tested on the Razerblade during the workshop. Also the navigation parameter for robot speed and goal tolerances were adapted for the usage of SLAM localization. At the end of the workshop the localization of the robot in the test garden in Renningen worked in principle but some improvements were still needed towards the navigation demonstration.

During the workshop the following topics were tested:

- SLAM: Mapping of the test garden in Renningen was successful. Two reconstructions are available. A sparse version usable for localization and a dense version usable for the registration with the GardenUI and the occupancy grid generation.
- SLAM: Localization in the Renningen test garden works but needs improvements towards the navigation demonstration.
- SLAM: The localization tests showed that the delay of the position estimation is still too high even on the Razerblade Laptop (some times several seconds). Thus a further speed up is needed.
- GardenUI: The semi-automated registration of the dense 3D point cloud from the SLAM mapping was tested and worked as expected.
- GardenUI: The occupancy grid generation based on the dense 3D point cloud from SLAM merged with the objects from GardenUI was successfully tested and an occupancy grid usable by the navigation software was created.
- Navigation: The navigation was able to plan a collision free path based on the occupancy grid for a given goal. The robot was also able to reach the goal along the path if the localization provides a stable robot position estimation. However, the parameters for the path following needs to be improved.

During the workshop, the following topics were identified as next steps.

- ◦ SLAM: Build 3D point clouds based on the data set recorded with closed blinds.
- ◦ SLAM: During the workshop a scaling issue for reconstruction was detected. This issue needs further investigation.
- ◦ SLAM: Analyze the run time problems of localization.

- SLAM: Position jumps of several meters were detected by visual inspection in the GUI during the localization tests. An analysis of these large position jumps during the localization has to be done.
- SLAM: The localization sometimes fails completely and no position of the robot is provided. These failures also have to be analysed in detail.
- Navigation: Path following needs parameter optimization. Currently the robot is wriggling along the given path.
- Navigation: Improve the navigation software to be able to deal with delayed pose estimates and SLAM localization failures.
- GardenUI: Register the 3D point cloud from the data set with closed blinds and create the occupancy grid for the navigation.
- All: Test overall system with all components GardenUI, Master-State-Machine, SLAM and Navigation.

4.6 System Integration and Demo Preparation

Location: Robert Bosch GmbH, 71272 Renningen, Germany

Date: 19. - 22. September 2017

Participants: Dominik Honegger (ETHZ), Johannes Schönberger (ETHZ), Marcel Geppet (ETHZ), Radim Tylecek (UEDIN) and Michael Blaich (BOSCH)

The aim of this integration workshop was to integrated and test the overall system required for the navigation demonstration. In the beginning of the workshop the improved SLAM localisation was tested and it showed that it was now running fast enough and more reliably. However, it turned out that the SLAM localization is quite sensitive to changing lighting conditions e.g. cloudy/sunny. Also changing shadows during sunny days may cause problems for the SLAM localization. For this reason, it was decided to record another mapping data set at the same time of day as the demo will take place. The recording of this further mapping data set was done during the workshop at a sunny day at noon. As for the navigation demonstration also sunny weather conditions are expected the camera parameters were optimized for sunny weather conditions. The integration of all components was also successful. The robot was able to localize in a map from the test garden and the position of the robot is displayed in the GardenUI and also provided to the navigation software. The robot was also able to reach a goal defined in the GardenUI while avoiding the obstacles mapped in the occupancy grind. Since all components were integrated and working during the workshop, a video of the navigation demo was recorded. The video is available at `https://www.youtube.com/watch?v=6R97-cb0K5M`. The focus for the video was on the mapping part of the SLAM pipeline and the registration of the 3D point cloud in the GardendUI because these parts takes to long to show them in an online demonstration. The entire setup for the navigation demonstration was also tested during the workshop. Figure 8 shows first tests with the demonstration setup using two large TV screens.

Figure 8: Impressions from the demo preparation workshop at the Bosch test garden in Renningen.

During the workshop the following topics were tested:

- SLAM: The SLAM localization was successfully tested on the data set for closed blinds when weather conditions were the same as those for mapping. However, for other weather conditions the SLAM localization was not reliable enough.
- GardenUI: The registration of the SLAM map in the GardenUI worked and goals for the navigation could be defined in the GardenUI. Also the occupancy grid generation worked well.
- Navigation: The master state machine and the navigation software were tested successful for the scenarios planned for the navigation demo.
- ALL: Test runs for the navigation demo were successful performed.
- ALL: Video sequences used to show the mapping and registration process were recorded.

During the workshop the next steps for a successful navigation demonstration were defined.

- ○ SLAM: Create 3D point clouds based on the sunny data set.
- ○ SLAM: Test the localization performance for the sunny data set.

5 Overview of State of Integration

The system integration for demonstrator 1 included the SLAM components for mapping and localization to the previously built map together with the GardenUI as user interface and the navigation components for navigation planning, navigation execution and the master state machine. With these components the demonstrator 1 is able to built a map from the test garden and then based on this map navigate to user defined goals in the test garden while avoiding known obstacles. The successful interaction between these components was shown in the navigation demonstration. A video of this demonstration is available at `https://www.youtube.com/watch?v=6R97-cb0K5M`.

Since the SLAM localization is not yet robust enough for a reliable navigation, further improvements need to be made to avoid large positional jumps during localization. For this, on the one hand, the localization itself will be improved and, on the other hand, an additional localization filter will be implemented to fuse information from IMU, odometry and the pose estimation from SLAM. Also the navigation software needs to be improved by integrating recovery behaviours for situations were the localization fails. The approaching to bushes and roses must also be improved so that the objects can later be trimmed by the robot. The GardenUI needs an extension so that the user can define the desired shape for the bush trimming.

Not yet integrated to the overall system are the components for Trimming, 3D Data Processing and Garden Object Detection. The next components which will be integrated into the overall system are the 3D Data Processing and the Garden Object Detection. In parallel the components for Trimming, SceneFlow, and the arm cameras will be integrated into a standalone subsystem for demonstrator 2. This demonstrator 2 will then be used for the second demonstration of fixed-arm trimming. After the demonstration, the integration of the subsystem from demonstrator 2 into the overall system will start.

