TrimBot2020 Deliverable D1.3

Platform 3: Carries the arm for demonstrator 3

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Dissemination: CO

Abstract: The platform 3 used for the final demonstrator 3 is based on a Bosch Indego lawn mower. The original mower, however, is heavily modified to be able to carry the arm. Several iterations were necessary to achieve the final design of the platform. This deliverable shows these steps and documents the final version of platform 3.

Deliverable due: Month 40

Contents

Todo list

1 Introduction

At the beginning of the project several meetings were held to find a vehicle / arm combination suitable for the TrimBot2020 project. After evaluating several robot / arm combination the decision was made to use a Kinove Jaco^2 arm (Figure 1b) and a robotic lawnmower Bosch Indego 1200 (Figure 1a) as vehicle basis. The criteria for the choice of the Kinova Jaco^2 arm were its light weight, the low power consumption and the integrated electronics which avoid an external control box. The arm selection is further explained in Deliverable D2.1. The selection criteria for the Indego as a vehicle base were – in addition to its good maneuverability – its size and weight, which are already very close to a possible product. However, making it possible to carry the arm with the Indego required extensive changes to the robotic lawnmower platform. These modifications were examined in two master theses [2, 1] and are summarized in Section 2.

The arm and camera integration into the modified vehicle is described in Section 2.4. As one of the reviewers suggested in the first review meeting the platform 3 prototype was duplicated. This duplication is documented in Section 4. A description of the power concept implemented for the prototype of platform 3 follows in Section 5. Reaching a trimming position close enough to the trimming object required visual servoing w.r.t. the trimming object. This visual servoing approach is documented in Section 6.

(a) (b)

Figure 1: Basic components used for demonstrator 3 prototype. (b) Kinova Jaco^2, (a) Robotic Lawnmower Bosch Indego 1200.

2 Vehicle Platform Design

Together with the decision to use the Kinova Javo arm (see D2.1 for more details), it was decided to use as vehicle basis the Bosch Indego 1200 robotic lawn mower as shown in Figure 1a. From the goal of the project several requirement were derived for the vehicle basis:

- carry arm and tools
- be able to drive through the garden with arm and tools mounted on the vehicle
- stay stable while trimming
- provide additional power for arm, tools and other electronics
- provide space for laptops
- integrate cameras as environment sensors

The plan was to fulfill all these requirements with a minimum of modifications to the Bosch Indego 1200 robotic lawn mower. However, it was also clear that modifications will be necessary to meet the requirements. First of all some payload studies were carried out. Based on these results a first concept for the demonstrator 3 prototype was designed and built. In the course of the project this first concept was further developed to the final demonstrator 3 prototype.

2.1 Payload Study

In order to check whether the concept with the Bosch Indego 1200 robotic lawn mower as basis for the vehicle was tenable, an evaluation of its expected payload carrying capacity was conducted. From the technical data of the Bosch Indego 1200 robotic lawn mower it is known that a maximum torque on the wheel axle of 6 Nm is available at minimum rated voltage of the batteries. Using this torque and the assumption that a slope of 10° has to be handled by the robot, allows to calculate the maximum possible payload for the robot with respect to the power train. For simplification the friction is neglected for the following calculations. First of all the force on one wheel F_w is calculated using the torque M_d and wheel radius r.

$$F_w = \frac{M_d}{r} \tag{1}$$

With torque M_d of 6 Nm and a wheel radius r of 0.075 m the resulting force on one wheel F_w is 80 N. To be able to move the robot on a slope of about 10° at least the downhill force has to be compensated. With this assumption a first approximation of the robot's total weight can be made using the equation for the downhill force F_d and the weight force F_g: Neglecting the friction losses and assuming that only one motor has to be able to drive the vehicle during a turning maneuver allows the assumption $F_d = F$:

$$F_d = F_g * \sin(\alpha) \tag{2}$$

where F_d is the downhill force, F_g is the weight force and α is the angle of the slope in radians. The weight force F_g can further be substituted by the product of mass m and acceleration due to gravity g. Applying this to Equation 2 gives the total mass m of the robot as:

$$m = \frac{F_d}{g * \sin(\alpha)} \tag{3}$$

With acceleration due to gravity of $9.81\,\mathrm{m/s^2}$ and a downhill force of $80\,\mathrm{N}$ that has to be compensated, the maximum total mass of the robot can be calculated as:

$$47.0\,\mathrm{kg} = \frac{80\,\mathrm{N}}{9.81\,\mathrm{m/s^2} * \sin(10^\circ * 3.14/180)} \tag{4}$$

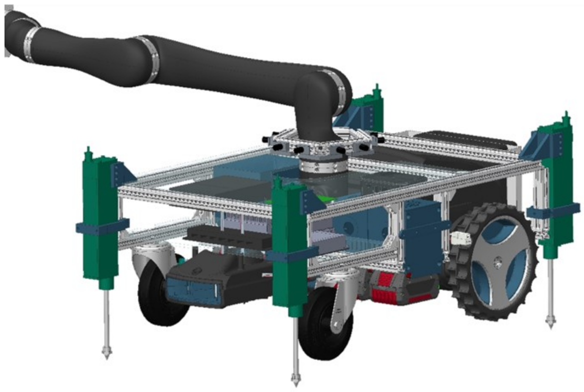
As the friction was neglected for this calculation the result is only a rough upper bound and the total weight of platform 3 should be less than $47.0\,\mathrm{kg}$.

In order to get a more precise upper bound for the total weight further tests were performed with the Bosch Indego 1200. In these field tests additional weights made of wood and aluminium plates were loaded on the Indego. This was used to determine the maximum payload at which the lawnmower was still able to drive reliably through the garden and up a slope. Figure 2 shows examples from these tests. The tests showed that the Indego was not able to drive properly with a total weight of about $43\,\mathrm{kg}$. Tests with smaller payloads showed that with a total weight of $36.5\,\mathrm{kg}$ the Indego is able to drive on soil, grass and also on small grass slops up to 10°. For pebble stones and wood chips it turned out that the Indego is not able to drive with additional payload. Thus, it was decided that the robot will only drive on grass and not on wood chips or pebble stones during the project. Being able to drive on wood chips or pebble stone as well would have required too extensive modifications of the platform. A more detailed description of these tests and an more detailed evaluation of the maximum payload is given in [2].

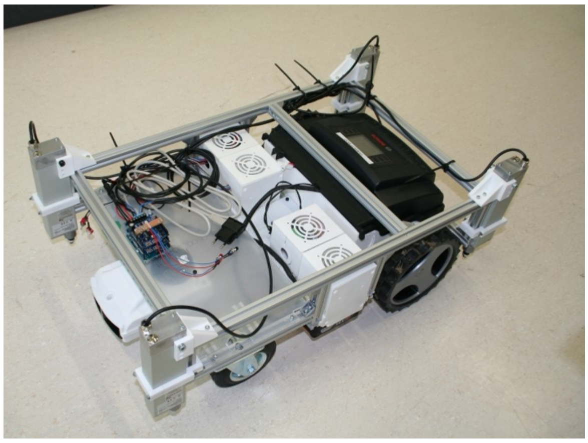
Figure 2: Platform 3 carries testing payloads made of aluminium and wood.

2.2 Initial Prototype Concept

After the successful payload tests, the modification of the Bosch Indego 1200 robotic lawn mower could start. The first step was to remove all unneeded parts e.g. the mowing unit to free space for TrimBot components such as the arm, additional batteries and electronics. It was also decided to use an additional aluminium frame to get a more rigid body. After initial research, it has been proven that it was best to keep only the drive unit of the mower and use a new aluminium frame of similar dimensions to the original robotic lawn mower. The first concept of the new frame is shown in Figure 3. In several consortium meetings the placement of the vehicle cameras was discussed and the decision was made to place them as close as possible around the arm due to limited cable lengths. More details about the vehicle camera setup are given in Section 2.4. There was also the idea to use additional stabilizers to stabilize the robot on the ground during trimming. The first concept featured stabilizers placed at each corner. A



(a)



(b)

Figure 3: First version of platform 3: (a) CAD model with arm and cameras. (b) Modified robotic lawn mower with aluminium frame and stabilizers.

CAD model of the first version of the prototype with the new aluminium frame, cameras placed around the arm and stabilizers at the corners is shown in Figure 3a. This version was built by Bosch for early field and integration tests. Figure 3b shows the initially built prototype without cameras and arm.

Based on this concept, an analysis of the actual weight of the robot was performed. This resulted in a total weight of about 28 kg. The analysis included drive unit, aluminium frame, arm, tool, electronics and some more smaller parts as shown in Figure 4. This analysis together with the evaluation of the maximum possible payload for the driving unit, showed that there is still enough capacity to transport laptops and other electronics on the prototype.

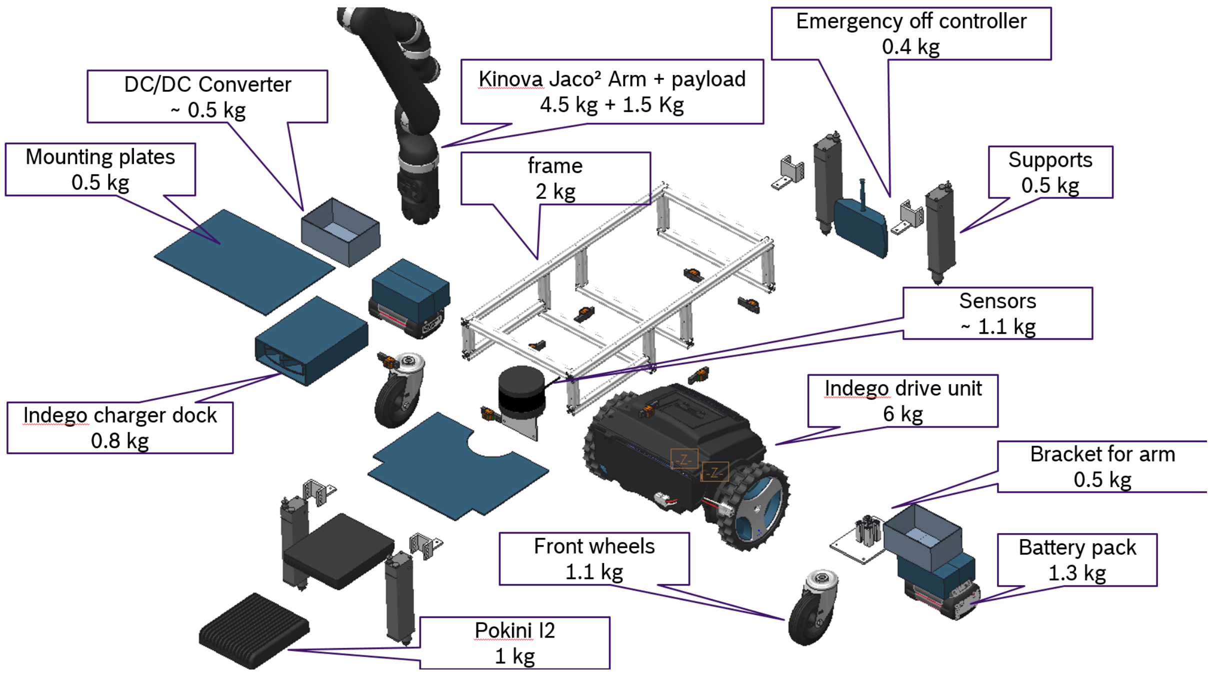
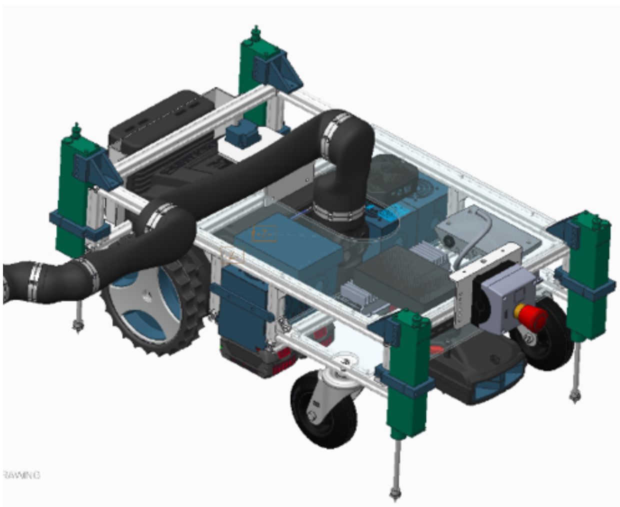


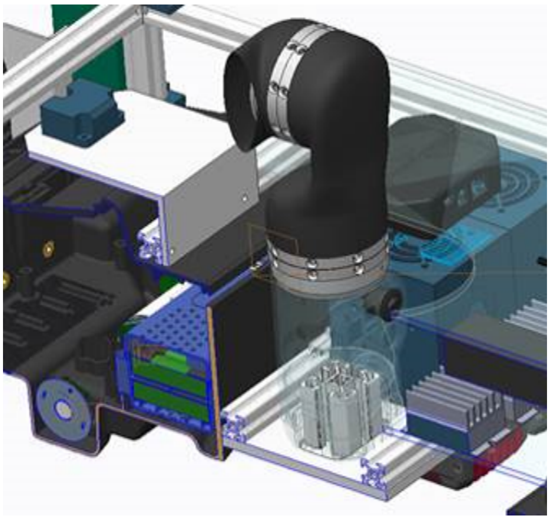
Figure 4

2.3 Arm Mounting

Three concepts for the arm mounting point on the vehicle were implemented: One with the arm at the front, one with the arm at the rear and one with the arm at the vehicle center. The evaluation of the concepts was presented and discussed at consortium meetings and is documented in [2]. The final decision was to place the arm in the center of the vehicle which gives the best stability and also the best weight distribution. For stability reasons as well another decision was made to place the arm as low as possible on the vehicle. Figure 5a shows the concept with the arm mounting point in the center of the vehicle. A detail view of the arm mounting point is shown in Figure 5b. A 40x40 mm Bosch profile is used as connection to the arm. This profile is fixed via an aluminium plate to the aluminium frame of the vehicle which ensures a rigid connection between vehicle and arm.



(a)

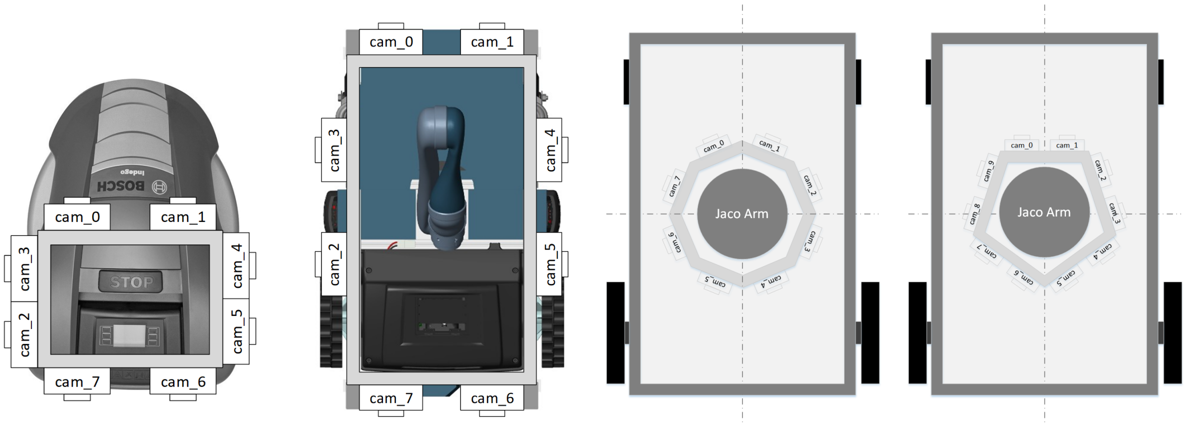


(b)

Figure 5: Arm mounting concept. (a) Overview with arm mounted in the center of the vehicle. (b) detail view of the connection between arm and vehicle frame.

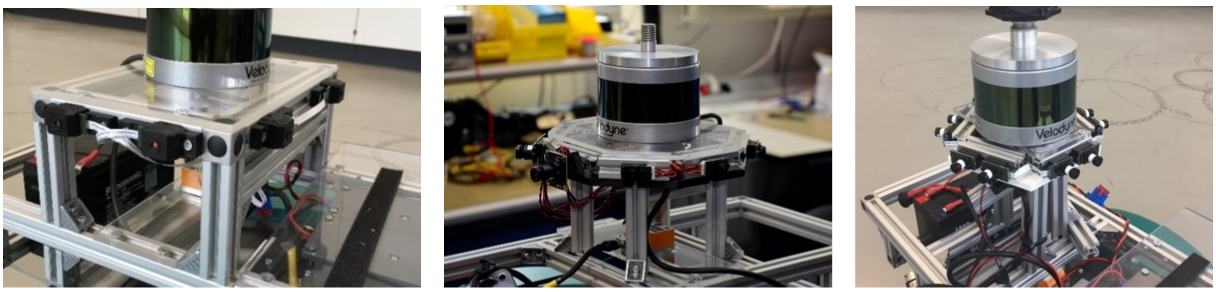
2.4 Camera Setup

Several iterations were needed to find the best solution for the vehicle camera setup. All stages of these iterations are shown in Figure 6. In the first version 4 stereo camera pairs were mounted on an small aluminium frame on top of the vehicle. This setup allowed look towards each side of the vehicle with a stereo camera. A sketch of this setup is shown in Figure 6a. The next iteration was to attach the cameras to the vehicle frame as shown in Figure 6b. However, this setup could not be realized due to limited camera cable lengths. The limited cable lengths led to the decision to place the cameras as close as possible around the arm to be able to connect all cameras to one FPGA. The result was an octagonal camera ring around the arm as illustrated in Figure 6c. With this setup a surround view of 360° was possible. It turned out, however, that the small overlap between the cameras causes problems for stereo vision applications. Thus, the final setup was a pentagonal camera ring around the arm with five stereo cameras as shown in Figure 6d.



(a) (b) (c) (d)

Figure 6: Iterations of the vehicle camera setup. (a) four stereo cameras on a senor tower. (b) four stereo cameras on the vehicle frame. (c) octagonal camera ring around the arm. (d) pentagonal camera ring around the arm with five stereo cameras.



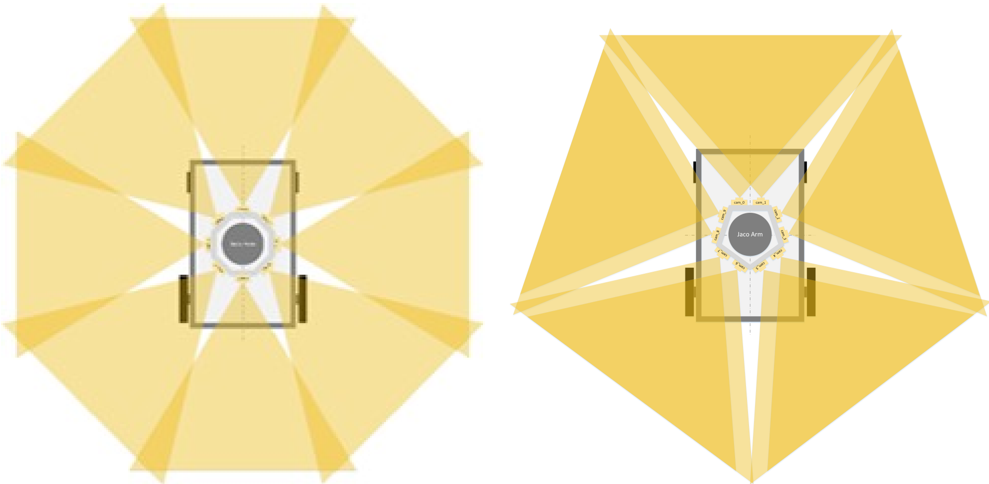
(a) (b) (c)

Figure 7: Camera setups used for data recordings in Wageningen. (a) four stereo cameras on the senor tower of platform 1. (b) octagonal camera ring mounted on platform 2. (c) pentagonal camera ring around the arm with five stereo cameras mounted on platform 2.

The concepts one, three and four were realized and tested on a TrimBot platform. Figure 7 shows these three cameras setups. Datasets for calibration and for driving around the garden in Wageningen are also available for all three setups.

From version three (octagonal setup) to version four (pentagonal setup) also the camera lenses were changed to wide angle lenses of about $55°$ to still obtain a surround view of $360°$. With this new setup an omni-directional stereo camera setup was achieved. A sketch of the cameras Field-of-View for the third and fourth concept are shown in Figure 8.

The decision to mount the arm on the vehicle as low as possible limits the maximum mounting height of the camera ring by the height of the first joint of the arm. This is because it must be ensured that the arm can also reach lower parts of the plant. Which in turn required adequate space to point downwards with the first arm joint. This, however, leads to an occlusion of the cameras by the aluminium frame of the vehicle. Figure 9 illustrates the occlusion to the front cameras caused by the vehicle frame. With this setup about one third of the front cameras' field of view was occluded by the vehicle. This results in a blind spot of about 1.0 m in front of the vehicle. In a consortium meeting it was then decided to stay with the pentagonal camera



(a) (b)

Figure 8: Cameras Field-of-View for the octagonal concept three (a) and the pentagonal concept four (b).

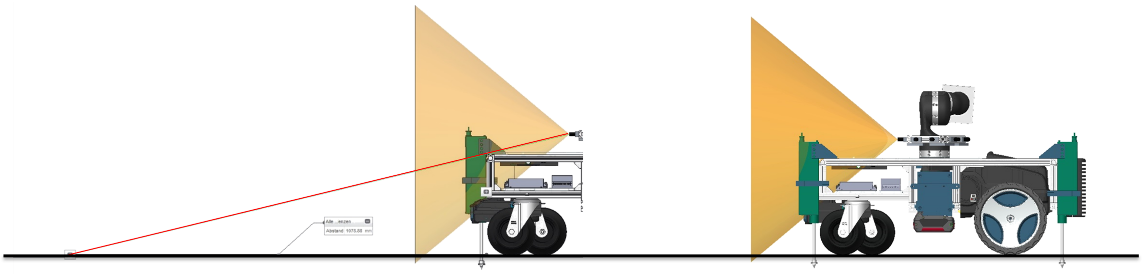


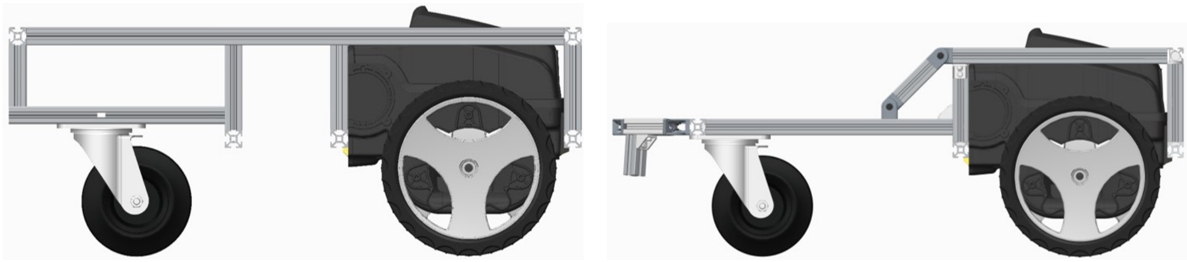
Figure 9: Illustration of the occlusion of the front cameras caused by the vehicle frame.

setup and revise the vehicle frame for the final version of demonstrator 3 in order to keep the occlusion as low as possible. Based on this decision the final design process for the vehicle was started. This included, in addition to the redesign of the aluminium frame, also a design of a camera housing. The final vehicle design was produced by Bosch and the camera housing design by WR.

2.5 Final Concept

Based on the decision to redesign the aluminium frame several further possibilities for improvement were identified:

- Modify aluminium frame to reduce the camera occlusion
- Improve accessibility of the additional batteries to make battery exchange more easy
- Improve stabilizers to stay more stable and detect ground contact
- Add a shell to protect electronics against light rain and dust

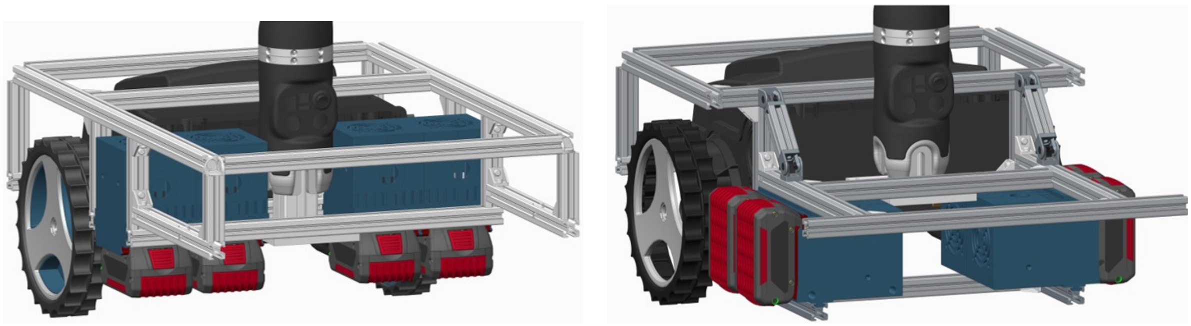


(a) (b)

Figure 10: Side views of vehicle aluminium frame for initial and improved concept. (a) initial concept of aluminium frame (b) improved aluminium frame used for the final version of platform 3.

These improvements were mainly examined in a Bachelor thesis [1]. Figure 10 shows side views of the initial and improved aluminium frame. The improved frame is lower then the first one, thereby reducing the occlusion for the front cameras to a minimum. A drawback of the new frame was the reduced space for electronics and laptops. To compensate this a decision was made to put the laptops on top of the drive unit, which causes a larger occlusion for the rear cameras. Seeing that the main direction of movement is forward, this was considered acceptable.

The second modification was to improve the accessibility to the additional batteries. These batteries are used to power arm, tools, Embedded PC and all the other electronics. Figure 11 shows both the initial and the improved battery integration. In the initial version the access to the batteries was below the vehicle. This made an exchange difficult. For the improved concept the batteries were moved to the side. This allows an easy access and a fast change of batteries.



(a) (b)

Figure 11: Placement of additional batteries. Initial concept (a) and improved concept (b).

The third improvement was about the stabilizers. There were two main changes compared to the initial concept. The first was to change the attachment of the stabilizers to the frame in order to achieve a small angle of inclination of about 5° to the outside. This small inclination angle of the stabilizers can be seen in Figure12. The second change was made on the inside of the stabilizers. Here, the original plastic lifting rod and bearings were replaced by a steel lifting rod with new bearings. For more details about the improved lifting rod and the bearings see [1]. Additional sensors were also integrated into the stabilizers to detect ground contact and determine the position of the lifting rod. Magnets were mounted to the spindle that extends the

(a) (b)

Figure 12: Final version of the platform 3 prototype without cover. (a) CAD model (b) Prototype built by Bosch.

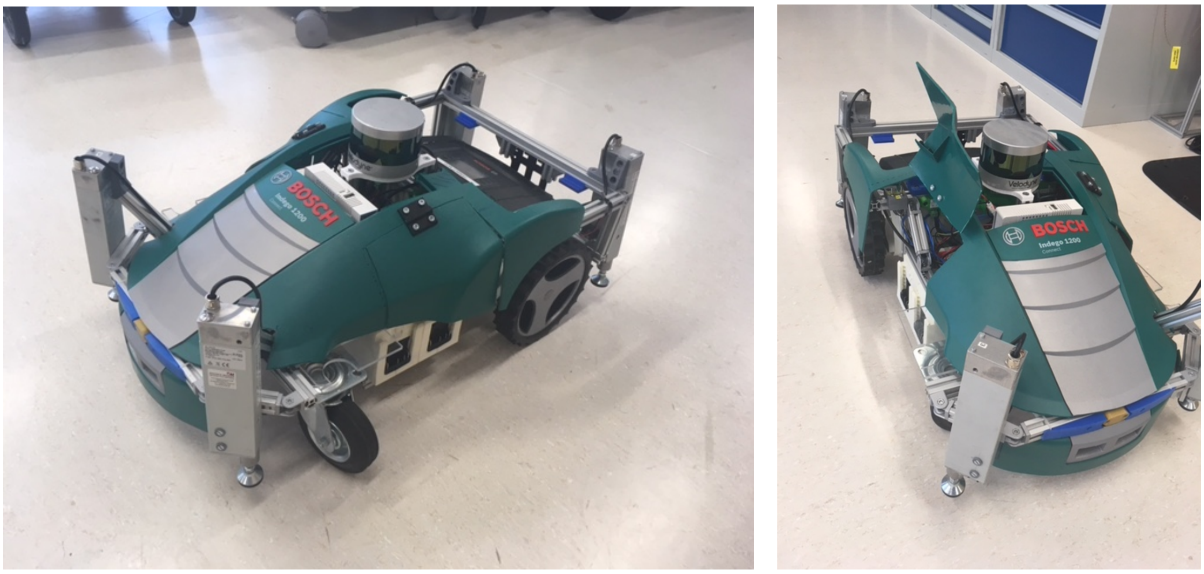
rod and a hall sensor was then used to count the rotations of the spindle. In combination with end stop switches and an initialization phase, which retracts the lifting rod to the upper end stop, the current position of the lifting rod could be determined continuously.

The idea for the ground contact detection was to detect it by an increase in the motor current. For this, the current sensing outputs of the H-bridges of the motor drivers were connected to an Arduino. An evaluation showed that the ground contact of the stabilizers causes a significant rise in the motor current. During the evaluation, a threshold for the motor current for ground contact detection could also be determined. As the Arduino was also used to control the stabilizers, the integration of stopping the stabilizers if the motor current threshold is reached was straightforward. By using the `rosserial_arduino`[1] library the Arduino was integrated into the overall software system. This allowed the master state machine or the remote control to be able to control the stabilizers.

A CAD model of the final concept showing the improved frame and stabilizer attachment is shown in Figure 12a. The initial prototype was modified accordingly. Figure 12b shows the modified version of the prototype. A mounting frame for the camera ring was also added to the prototype for an easier camera integration.

As Figure 12b shows, most electronics were freely accessible. This simplified the integration but also had disadvantages in terms of possible damage. In order to give a better protection against mechanical damage, light rain and dust, the original shell of the Bosch Indego 1200 was adapted to fit the TrimBot prototype. For this purpose, recesses were made for the new aluminium frame and the front stabilizers. Some flaps were also integrated to have easy access to the additional batteries. Figure 13 shows the final concept of demonstrator 3 without arm but with the modified shell. In this version a Velodyne VLP16 Lidar was installed for navigation testing at the spot where the arm would be placed later. For the final integration of cameras and arm the Velodyne was then removed. This version of the prototype was also the basis for duplication of demonstrator 3.

[1] `http://wiki.ros.org/rosserial_arduino`



(a) (b)

Figure 13: Final concept for platform 3 vehicle. (a) prototype with modified shell (b) modified shell with open flaps for battery exchange.

3 Arm and Camera Integration

After the iterations for vehicle and camera design were finished, the arm and camera integration was a straight forward process. Mechanically both were easily mounted to the intended frames. The electrical mounting was also plug and play because both cameras and arm are connected via USB to the laptops. The arm itself could be powered by the DC-DC converter for 24 V that had already been integrated for the stabilizers. More details about the arm integration are given in D6.4 *(System integration for demonstrator 3)*. More details about the power concept are given in Section 5. Figure 14 shows some photos of the first time the arm was integrated into the demonstrator 3 vehicle. During these tests the arm was powered from the additional batteries and remote controlled by an operator. At this stage the final cameras were not integrated yet because they were used on the platform 2 and the integration into platform 3 was planned for a later workshop. Only a spare camera ring without housing was mounted in front of the arm for a few tests.

Figure 14: Platform 3 carries arm with bush trimming tool.

4 Platform Duplication

At the first review meeting one of the reviewers suggested building a duplicate of the final demonstrator. The consortium gladly accepted this proposal and decided to create a duplicate of platform 3. It was also decided that the second prototype should remain in Wageningen and therefore additional budget was transfered to WR. Bosch delivered all CAD models and part lists to WR and all needed parts were purchased from the additional budget. For the construction of the duplicate, Bosch and WR worked closely together. Figure 15 shows both prototypes of platform 3 during a construction meeting in Wagenignen. On the left hand side is the duplicate and on the right hand side is the original prototype is shown.

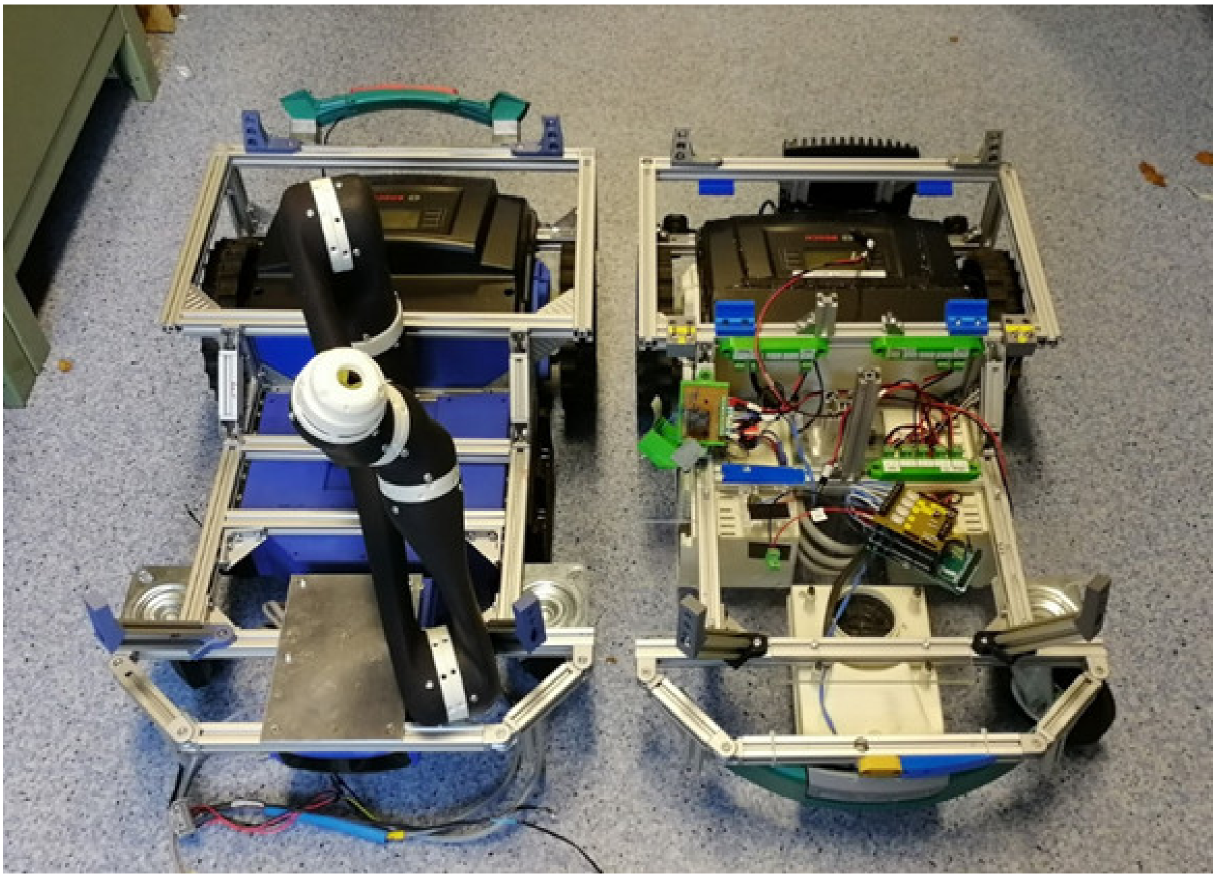


Figure 15: Photo from a construction workshop in Wageningen where the mechanical duplication of platform 3 was finished. Next step was to integrate the electronics into the duplicate (left: duplicate, right: original).

As can be seen in Figure 15 (right) a lot of the additional electronics was mounted directly to the base plate for the original platform 3. This made access easier and was a great advantage during the development of platform 3. However, it also caused problems with all the cables and the weak protection of the electronics. Thus, for the duplication the decision was made to improve the casing of the additional electronic components. To this end the electronics housing in the middle of the prototype, which connects the extra batteries, has been enlarged to include all other electronic components as well.

For the final demo the decision was made to equip one of the platforms with the rose clipping tool and the other one with the topiary trimming tool. Apart from that, both prototypes have the same abilities, so in case of a damage at one, a change to the other one is possible. Another benefit of the duplication is that both prototypes can be used equally for the integration process. Figure 16 shows the finale version of both platform 3 prototypes, both with camera ring and arm and tool. The left one is equipped with the rose clipping tool and the right one with the topiary trimming tool. The shell was removed for the demo to have a better access to the batteries, network switch and the laptops.

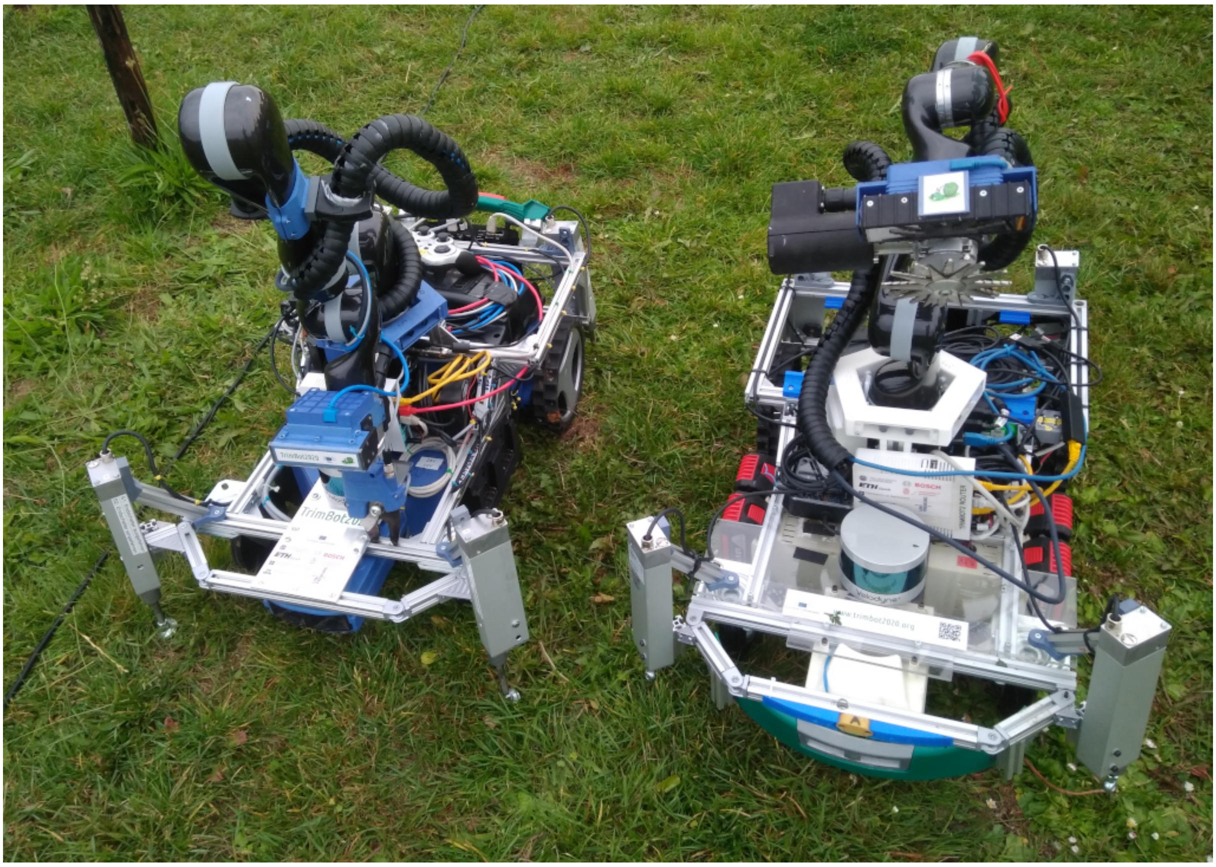


Figure 16: Final version of both platform 3 prototypes. (left) with rose clipping tool, (right) with topiary trimming tool.

5 Power Concept

The power concept for the demonstrator 3 prototype included four different voltage levels (36 V, 24 V, 12 V and 5,1 V) converted out of the additional batteries. The vehicle design described in Section 2 had enough space for four 18 V Bosch standard power tools batteries. Of these four batteries, two were then connected in series to deliver a voltage of 36 V and two were connected in parallel to allow a hot swap between the two. DC-DC converters were then used to produce the other voltage levels from these sources. The drive unit was completely separated from the rest of the power concept. For the drive unit the original batteries and electronics were kept. This enabled the use of the Bosch Indego 1200 docking station for charging the base unit. Figure 17 shows an overview of the power concept.

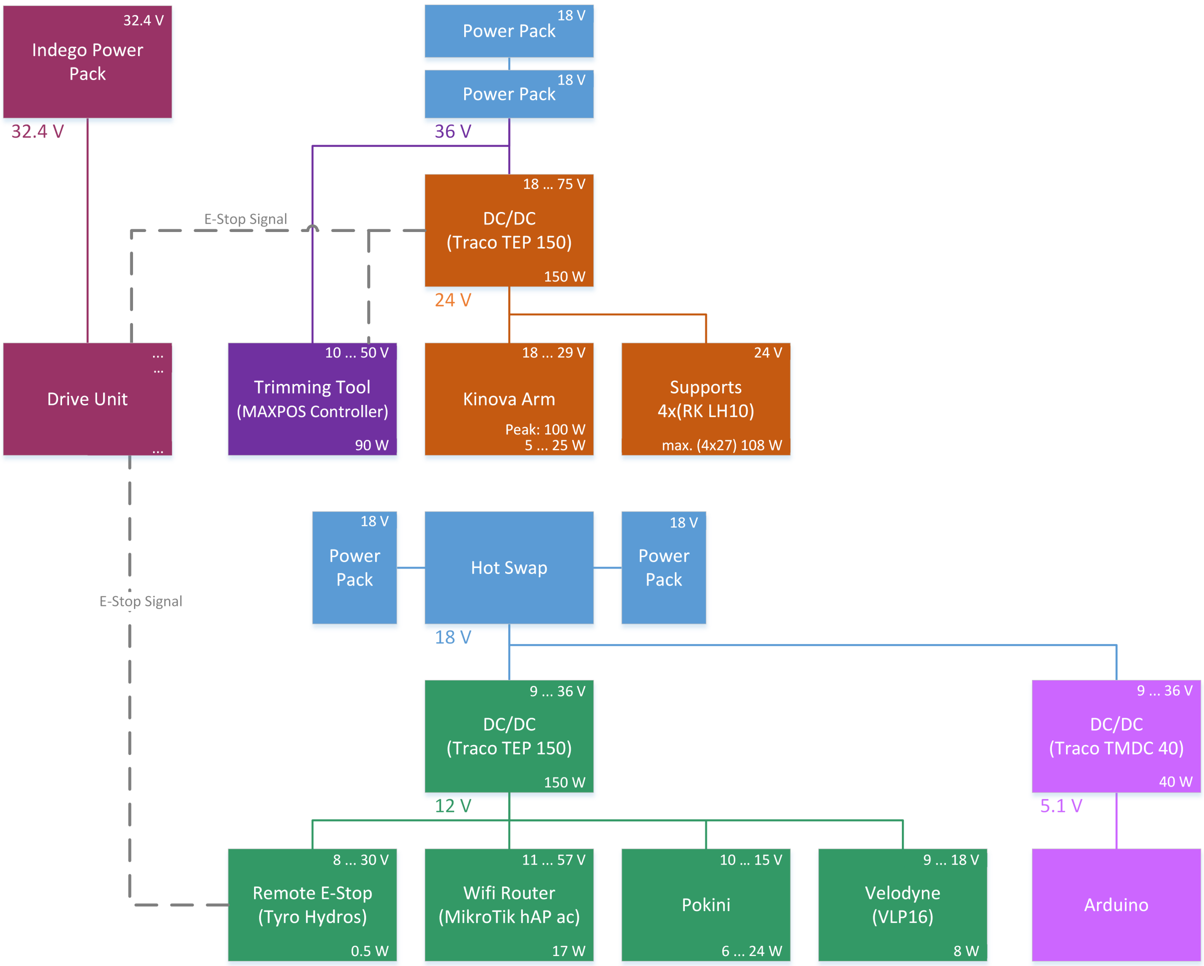


Figure 17: Power concept for platform 3.

The Maxon motor controller (MAXPOS) used for the tool control was directly connected to the 36 V level because it could handle an input voltage from 10 to 50 V. To power the Kinova Jaco arm and the stabilizers, a DC-DC converter (Traco TEP 150) was integrated to convert the 36 V to 24 V.

Two other DC-DC converters (Traco TEP 150, Traco TMDC 40) were connected to the parallel 18 V batteries to reduce the voltage to 12 V and 5.1 V, respectively. The Pokini embedded PC, the Wifi Router, the remote emergency stop receiver and the Velodyne Lidar were connected to the 12 V circuit. The Arduino for stabilizer control was connected to the 5.1 V circuit.

For the remote emergency stop the signal from the receiver was connected to the drive unit emergency stop of the vehicle and to the MAXPOS controller for stopping the tool. The initial idea for stopping the arm was to cut the power of the arm by simply switching off its DC-DC converter. However, in first tests it turned out that switching off the power of the arm will cause the arm to crash, because without power it will just drop due to gravity. Thus, a time relay was integrated in the emergency stop circuit that only cuts off the power to the arm for a few milliseconds. This then stops the arm and holds it in the last position, with only a very minimal drop. A reset of the arm is then required to be able to move it again.

6 Vehicle Servoing

In contrast to the statements of previous consortium meetings, that visual vehicle servoing will not be necessary due to a robust SLAM localization, the decision was made at the consortium meeting in Wageningen on 12.02.2019 to use visual vehicle servoing to move the robot to the trimming position. This decision was made as SLAM would not be able to achieve the required accuracy. The partner from ALUF agreed to take over the responsibility for the visual components for a visual vehicle servoing approach and Bosch took over implementing the vehicle control.

The idea of visual vehicle servoing is to place the vehicle at defined trimming positions w.r.t. the trimming object. The vehicle cameras should be used to detected the trimming object and estimate its position w.r.t. the vehicle. Thus, the vehicle can then be controlled w.r.t. this object. The global localization w.r.t. the garden map (SLAM) is used to navigate the TrimBot through the garden and move it in front of the trimming object at a distance of about 1.5 m. It is also required that the trimming object is visible in front camera pair of the vehicle. Thus, the robot has to be aligned accordingly at the end of the navigation process. Figure 18 illustrates this approach.

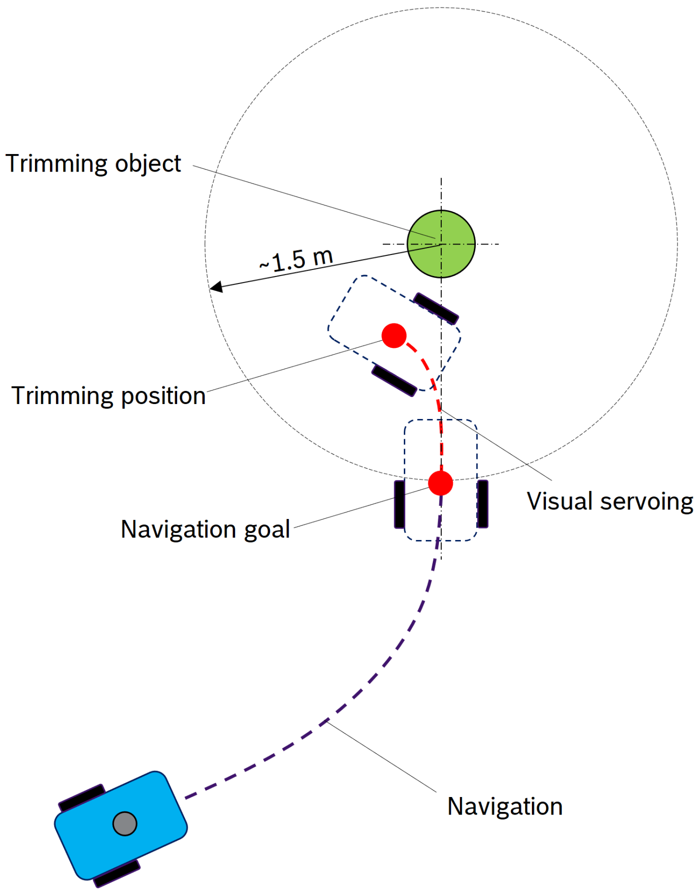


Figure 18: Sketch to show interaction between navigation and visual servoing.

Since it is not possible with the selected arm to completely trim a bush from one position, the TrimBot has to be able to approach several positions around the bush. A concept was first developed to achieve a simple and robust solution which handles both the approaching of objects and the circling around objects. The concept was then presented at the next consortium meeting in Edinburgh and was evaluated in further integration workshops in Renningen by Bosch and ALUF. In the following this concept is further explained.

6.1 Visual Servoing Concept

To make the visual vehicle servoing as simple as possible, it was split into two parts: The visual object detection and tracking as well as vehicle control. The team from ALUF was responsible for the object detection and tracking and Bosch for the vehicle controllers. The interface between visual object detection and tracking and the vehicle controllers is the TrimBot `VisualServoObject` ROS message.

The approaching of a trimming position was independently solved for object approaching and circling around a bush. To simplify the first task of approaching the first trimming position the procedure was further divided into two steps as illustrated in Figure 19. The first step is to drive straight towards the object until a desired distance is reached. In this step the vehicle controller tries to hold the object in the center of the front cameras and controls the distance to the object while stopping when a desired distance is reached. In the second step the vehicle then turns on the spot to have the bush at its side within a trimming distance of e.g. 0.80 m. The trimming distance is composed of the distance from the center of the arm to the edge of the bush (e.g. 0.65 m) and the radius of the bush (e.g. 0.15 m). The distance from the center of the arm to the edge of the bush is given by the trimming component and takes into account that the arm with the trimming tool has to fit between the vehicle and the bush. The radius of the object is estimated by the visual object detection. One challenge for the visual servoing in this step is that the trimming object moves from the front camera pair to the side camera pair.

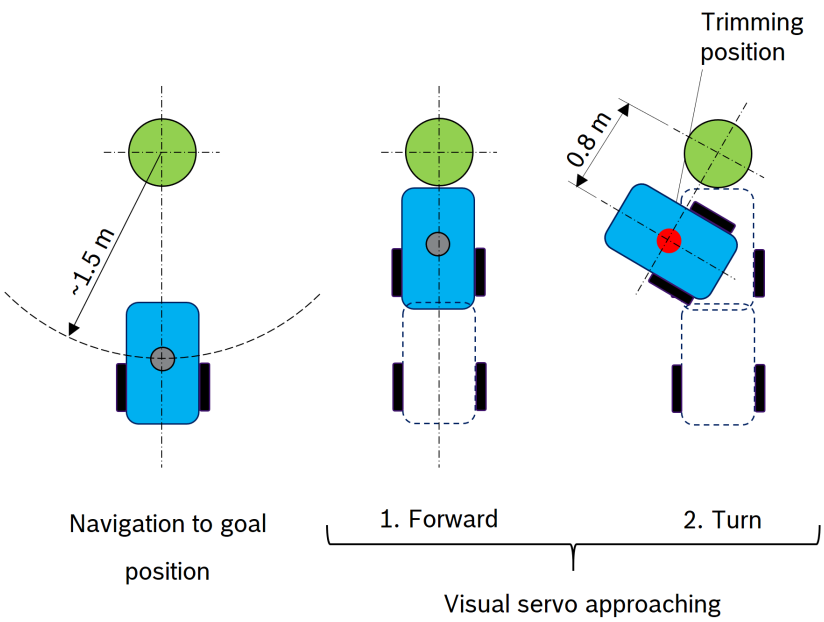


Figure 19: Approaching the first trimming position in two steps. First, drive straight ahead to the object. Second, turn to have the object perpendicular to the arm.

The second task for the visual vehicle servoing is to drive the TrimBot in a circle around a bush to further trimming positions. The trimming state machine gives the number of needed trimming positions for the object after scanning it. Thus, after successful trimming from the first trimming position the master state machine starts the visual servoing for circling around the bush to the next position. For this to work, the angle and the distance between the vehicle and the bush have to be controlled in such a way that the next trimming position is reached. The distance to the object (e.g. 0.80 m) for this new trimming position needs to be the same as for the first trimming position and the reachability of the object needs to be ensured by positioning the TrimBot to its side. Figure 20 illustrates the visual vehicle servoing for circling around a bush.

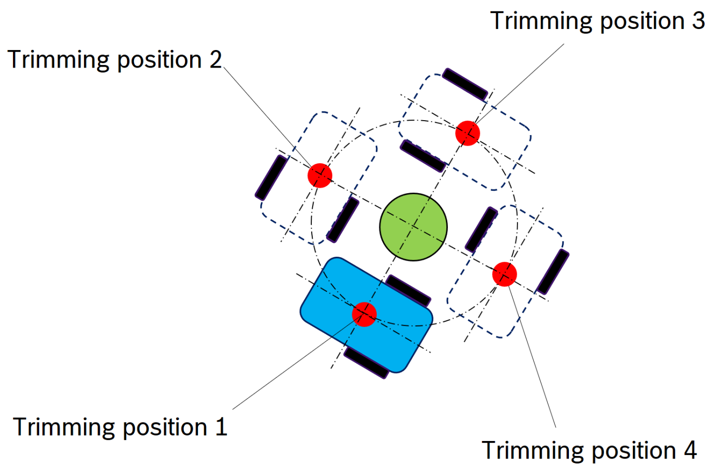


Figure 20: Drive in a circle around a bush to reach several trimming positions.

On the vision side there were two concepts for how to detect and track the trimming object. The first one was based on dispNet with additional object tracking and the other was based on deepTAM. First tests in Renningen showed that the approach based on dispNet had more problems when the object moved from the front cameras to the side cameras. Thus, the decision was made during the workshop in Renningen to use the deepTAM approach to estimate the position of the trimming object w.r.t. the vehicle.

6.2 Interfaces

For the integration of visual vehicle servoing into the master state machine all components had to implement on/off and pause actions via the `OnOff.action`[2] action. These were required on the one hand for the master state machine control flow – e.g. starting the bush detection only when the vehicle was actually positioned in front of the bush. On the other hand, the resource-intensive visual processing parts of the pipeline had to be started only on demand and stopped when not needed anymore. deepTAM was also required to be paused instead of stopped while trimming so that it would not lose its internal representation of the bush.

[2] `https://gitlab.inf.ed.ac.uk/TrimBot2020/trimbot_msgs/blob/master/trimbot_actions/action/OnOff.action`

The interface between visual object detection and tracking and the vehicle controllers is the TrimBot message `VisualServoObject`[3]. This message includes the distance to the object's center in meters, the diameter of the object in meters and the angle to the object in rad. The distance and the angle to the object are estimated w.r.t. the sensor frame, which is the frame of the left front camera.

6.3 Vehicle Controllers

In order to keep the process control in the master state machine simple, two vehicle controllers were implemented. One for the object approaching and one for circling around the object. The master state machine activates the controller depending on the needs of the main process flow.

For both controllers simple PID controllers were implemented where the distance and the angle between vehicle and trimming object were controlled. The outputs of the controllers are linear and angular velocity for the vehicle.

6.4 Visual Object Detection and Tracking

The visual servoing uses DispNet[3] for 3D perception and DeepTAM[4] for visual tracking. It provides the relative distance and angle of the robot w.r.t. the targe bush for vehicle controlling. Fig. 21 shows a software overview of the visual servoing part.

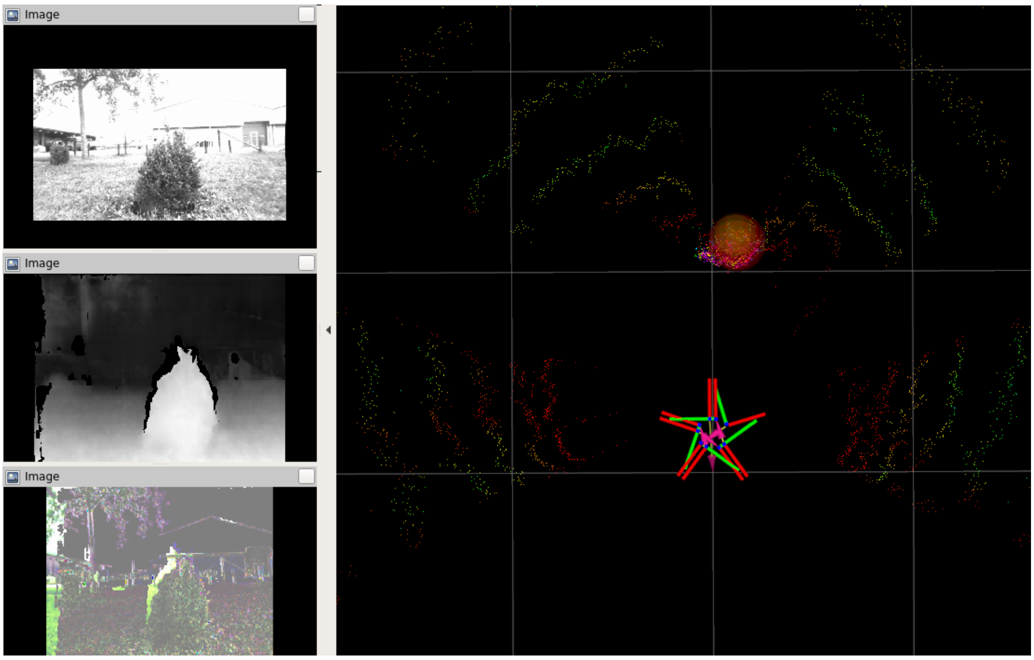


Figure 21: Visual servoing software visualization with active camera, DispNet depth and DeepTAM tracking images. The robot is shown as a star, consisting of 5 stereo pairs. The detected bush is marked as a red marker.

[3] `https://gitlab.inf.ed.ac.uk/TrimBot2020/trimbot_msgs/blob/master/trimbot_msgs/msg/VisualServoObject.msg`

Bush detection When the robot is localized relatively close to the bush with the camera facing the bush, we first estimate the disparity with DispNet[3] and then compute the 3D point clouds. To detect the bush from the point clouds, we remove the points on the ground by thresholding along the vertical axis. There is also a chance where the stabilizer or the cables on the vehicle platform falls into the view of the camera, therefore a rejection of too close points is also required. From the filtered point clouds we select the median of the 20 closest points to be the detected closest bush point $P_{closest}$. We initialize the bush center as $P_{closest} + R_{bush} \cdot t_{cam2bush}$, where R_{bush} is the given bush radius and $t_{cam2bush}$ is the direction from the camera center to the closest bush point. With this initialization we perform a least square sphere fitting on the point clouds of interest to get a more accurate bush center estimation. For robustness we use the smooth approximation of L1 loss: $L(z) = 2 \times ((1 + z)^{0.5} - 1)$.

Visual tracking To keep tracking the bush center we use DeepTAM[4], which is a keyframe-based visual tracking method with neural networks. When a new keyframe is generated, it will be only added to the point clouds of interest for bush center location estimation if the bush is within a good angle and distance range. In the circling task, the bush is completely out of the front camera view as shown in Fig. 22. It increases the difficulty for visual tracking. To eliminate the drift error, we designed a camera pair switching function to make use of the right camera pair during circling.

(a) (b)

Figure 22: (a) Front camera view during circling. (b) Right camera view during circling.

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