Safe Human-Robot Cooperation with high payload robots in industrial applications SAPARO

Deliverable 7.1 – Experimental results

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1 Introduction

This document aims in presenting a summary as well as insights and results of the development, implementation and execution of the SAPARO experiment. The main objective of the experiment was the implementation of a novel safety concept for monitoring human-robot cooperative workplaces. Here, we focus on workplaces in industrial applications with high payload robots.

Current research and developments regarding safety systems aim on safeguarding human-robot collaboration applications that use small robots such as the KUKA iiwa, Universal Robots UR5, and others. The payload capacity of these robots is limited to between 5-14 kg. However, many industrial applications where human-robot- cooperation would be very beneficial require higher payload capacity and robots with large workspaces, especially when considered against the background of demographic change and the corresponding challenge of improving the ergonomics for the worker.

The innovative and trendsetting solution for safeguarding these workplaces addresses both hard[1]- and soft- safety[2] considerations through a combination of safeguarding technologies. This consists of a tactile floor with spatial resolution as a hard-safety sensor for workspace monitoring together with a projection system as a soft-safety component to visualize user-beneficial information like the boundaries of the safety zones, process hints or next robot movements. In this experiment we will use and combine these technologies for the first time with the aim to safeguard the human while cooperating with high payload robots.

On basis of these technologies we further develop and implement algorithms to dynamically define the safety zones around the robot depending on its actual movements. These safety zones will be monitored by the tactile floor and visualized by the projection system. The safety zone will be generated online according to the relevant guidelines in ISO/TS 15066.

Besides using the current robot's joint angles and velocities for dynamically determining the size of the safety zone, the SAPARO experiment additionally incorporates the human's behavior. Using the spatial sensor information of the tactile floor the human's movement direction and speed is estimated. With this, the proposed safety concept fulfills all requirements of a "speed and separation monitoring" system.

In contrast to current fenceless safeguarding technologies such as laser scanners and camera-based workspace monitoring, which have static safety zones, our proposed dynamic safety zones will offer a maximum of free space around the robot and increases the robot availability, ergonomics and user acceptance. Furthermore, the tactile floor allows a user interaction with the robot or system by providing special interaction areas. If the human enters theses interaction areas predefined functionalities like robot movements or task control are executed. Additionally, the projection system provides the possibilities to visualize arbitrary information directly into the workspace of the user. Safety-specific, robot-specific or process-specific information can be visualized to inform, support and assist the user at work.

In the following sections we will describe the developments and results of the SAPARO experiment in more detail.

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[1] Hard-safety: Safety components (sensors, controllers, robots) that fulfill all requirements to be considered "certified" technology according to the current standards for general machine safety, functional safety, and for guards and protective devices

[2] Soft-safety: Aspects such as human factors, ergonomics and psychology, with the goal of enhancing the interaction, reducing robot stops raising the productivity of the human-robot team, as well as to increase human acceptance of the robotic system

2 Workplace setup and scenario

The human robot shared workspace was designed to have a size of 4.0 by 6.0 meters (see figure 1) that is sufficient to develop and evaluate the proposed safety concept and to demonstrate the dynamics of the safety zones as well as to allow an estimation of the human's behavior. In more detail, we specified the resolution of the tactile floor to 0.125 by 0.125 meters of a single sensor cell and adjusted them to detect contacts at a minimum weight of 10 kilograms. These detection and resolution capabilities are well-suited to robustly detect the footprints of humans.

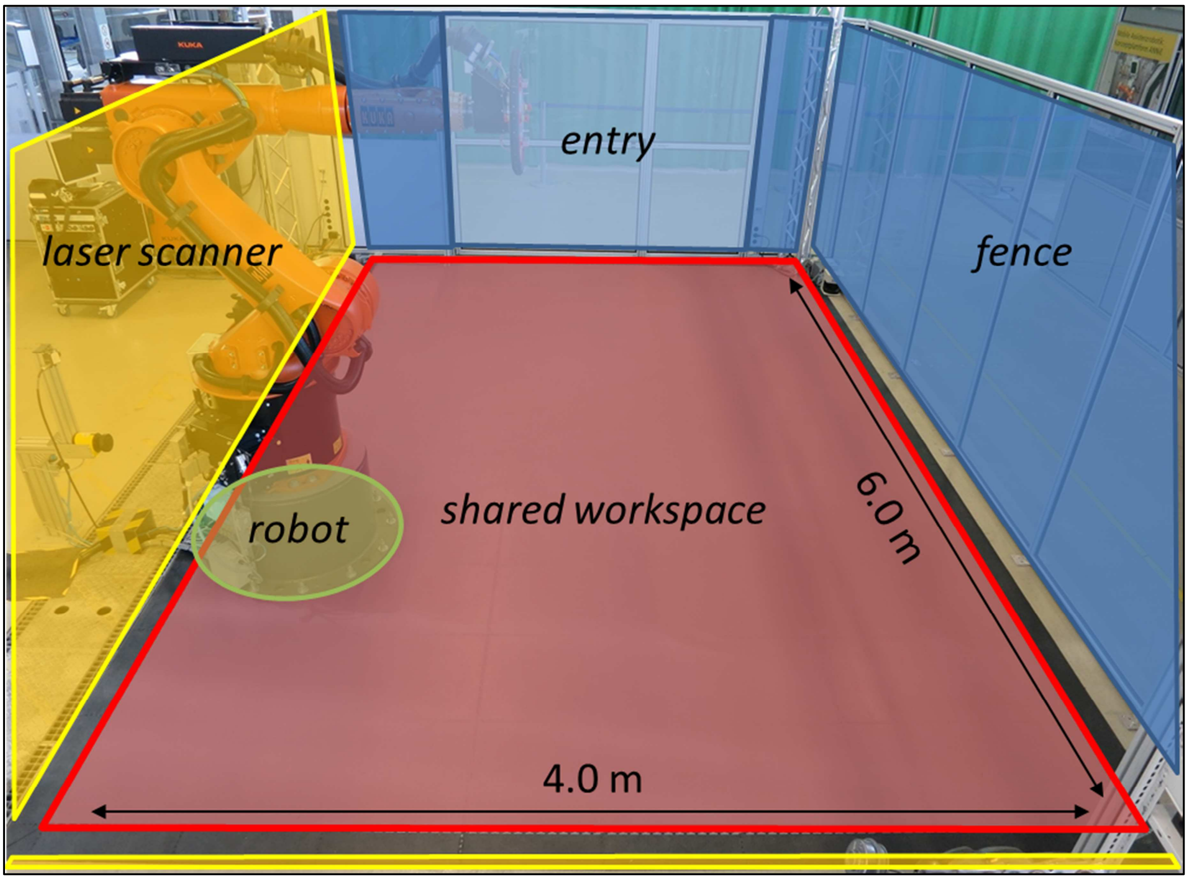


Figure 1: Human-robot shared workplace with a KUKA KR60 and a dimension of 4.0 by 6.0 meters.

As the proposed safety concept is not certified yet we needed additional safety equipment for safeguarding the shared workplace at development and demonstration stage. As depicted in figure 1, two sides of the workspace are enclosed by fences (blue-colored) while the front side is additionally equipped with a door to access the human-robot workspace. The other two sides are fenceless (yellow-colored) but safeguarded by safety laser.

The robot used in our workplace is a KUKA KR60 L45 that is able to handle 45 kg by a maximum range of 2.23 meters. The robot is positioned at the mid-left area of the tactile floor that is an ideal position for the planned scenario (see figure 1).

The tactile floor was developed with the aim of an easy and fast buildup as well as simple integration. So, we designed the tactile floor in a way that it consists of single quadratic tiles that include 4 by 4 sensor cells. The individual tiles can be easily interconnected by conductor band and allow a fast buildup of the entire floor. Altogether we needed 8 by 12 tiles to cover the entire area of 4.0 by 6.0 meters. In summary we implemented 96 tiles with 1536 sensor cells altogether. The buildup of the entire tactile floor took one day. In the following pictures the buildup of the tactile floor is illustrated.

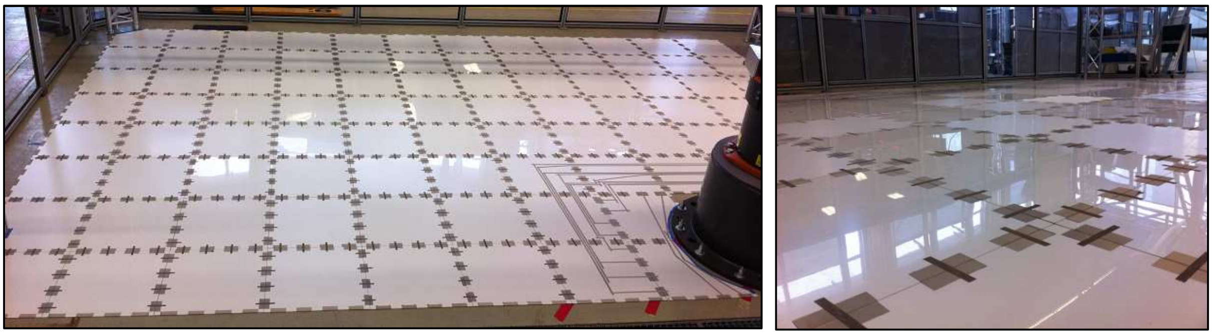
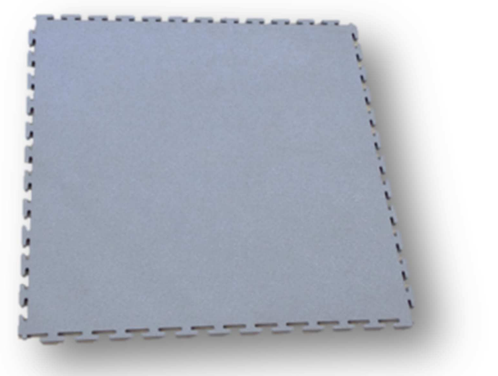


Figure 2: Setup of the tactile floor that comprises 96 quadratic tiles with 1536 sensor cells altogether.

The pictures in figure 2 show the individual sensor tiles that were placed one another. After connecting the sensor tiles by conductor band they were covered by industrial grade mats to protect the sensor layer against damage. Using these mats the tactile floor is robust concerning heavy objects and even vehicles. A single industrial mat and the resulting covering of the entire tactile floor are depicted in figure 3.



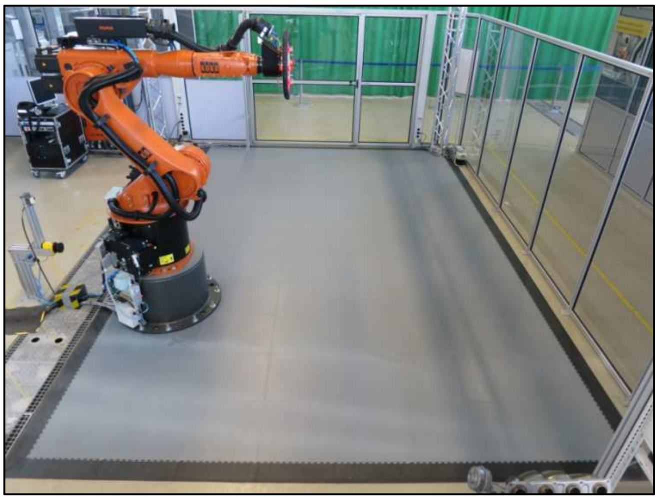


Figure 3: Industrial grade mat (left) and resulting covering of the entire tactile floor (right).

Besides the physical setup we developed and implemented a controller board (see figure 4) for managing the sensor cells. This electronics is responsible to control the single sensor cells and to acquire the sensor data of every sensor cell and provides these data via USB to the computing hardware. This board provides additionally several sensor-specific adjustments like the thresholding of the trigger signal of a sensor cell at detected contact. Actually, the controller board provides the data of all sensor cells at a rate of about 35 Hz. Here, we already identified major improvements to allow higher rates that will be implemented in future developments.

Figure 4: Developed controller board for collecting sensor data and communicate with computing hardware by USB.

Besides monitoring the shared workplace by the tactile floor the second technology of the proposed safety concept is a projection-based visualization system. This will be used to visualize safety-specific, system-specific or robot-specific information to the user by directly projecting this information into the shared human-robot workplace. For illuminating the entire workspace of 4.0 by 6.0 meters a minimum of 4 projectors were necessary that were mounted on a system carrier in a height of about 4 meters (see figure 5). The projectors feature a resolution of 1280 by 800 pixels and have an illumination intensity of 4000 lumen that is sufficient to project graphics, images and text with high resolution and that is further bright enough to see them despite additional external illumination. The projectors were connected by HDMI cables to a NVIDIA NVS 510 graphics card that allow a time synchronized image projection of all 4 projectors. As we want to visualize dynamically changed images, artefacts at projector-image boundaries can be avoided by this way.

Figure 5: System carrier and mounted projectors in about 4 meters height above the human-robot workplace.

We further planned an industry-oriented human-robot cooperation scenario that aims on supporting the human while assembling a turbocharger and motor block. Here, the turbocharger (see figure 6, left) has to be equipped on a motor block (see figure 6, right).

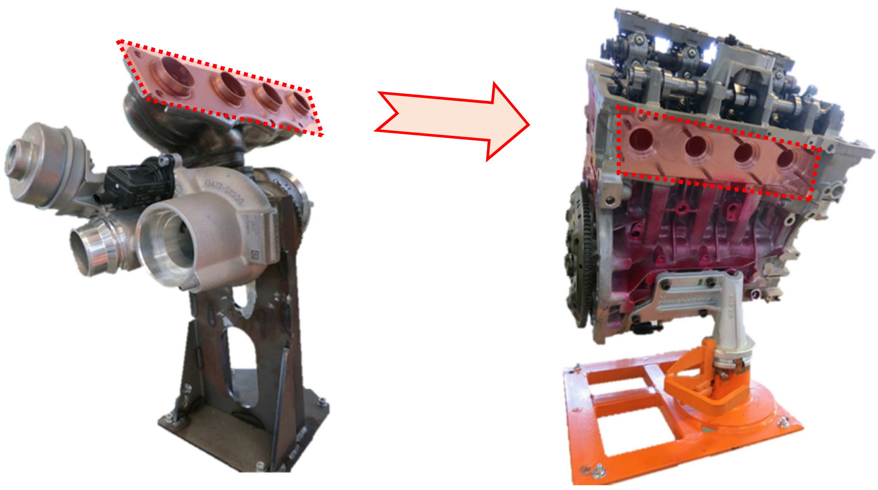


Figure 6: The scenario comprises the assembly of a turbocharger (left) and motor block (right).

The focus is on safeguarding the human by the tactile floor while the robot is moving autonomously. The dynamically adapted safety zones are visualized by the projection system any time. We further implemented a collaboration task that allows a sensitive control of the robot by hand guidance. The user is able to fine position the robot's gripper system for grasping the turbocharger that lies inside a box. The confirmation (work finished) and start of single tasks (move workpiece to destination position) or commands (open/ close gripper) can be done by interactive control buttons on the tactile floor visualized as symbols by the projection system. This allows an intuitive and easy control by foot without any additional hardware. Figure 7 depicts the single steps of the scenario:

1. Autonomous movement of the robot to grasp position
   The robot moves autonomously from its initial position to the grasp position. While the robot moves the safety zones are dynamically established and monitored by the tactile floor. If the human enters the warn zone or critical zone, the robot slows down or stops entirely.

2. Hand-guiding the robot and grasping the turbo-charger
   The human guides the robot and fine-positions the gripper system at the turbocharger. After that, the human activates the gripping by an interactive control button. The robot grips the turbocharger and starts moving to the motor block.

3. Autonomous movement of the robot to motor block
   The robot moves autonomously to the motor block and the corresponding safety zones are established. If the human enters the warn zone or critical zone, the robot slows down or stops entirely. Finally, the robot aligns the turbocharger at the motor block.

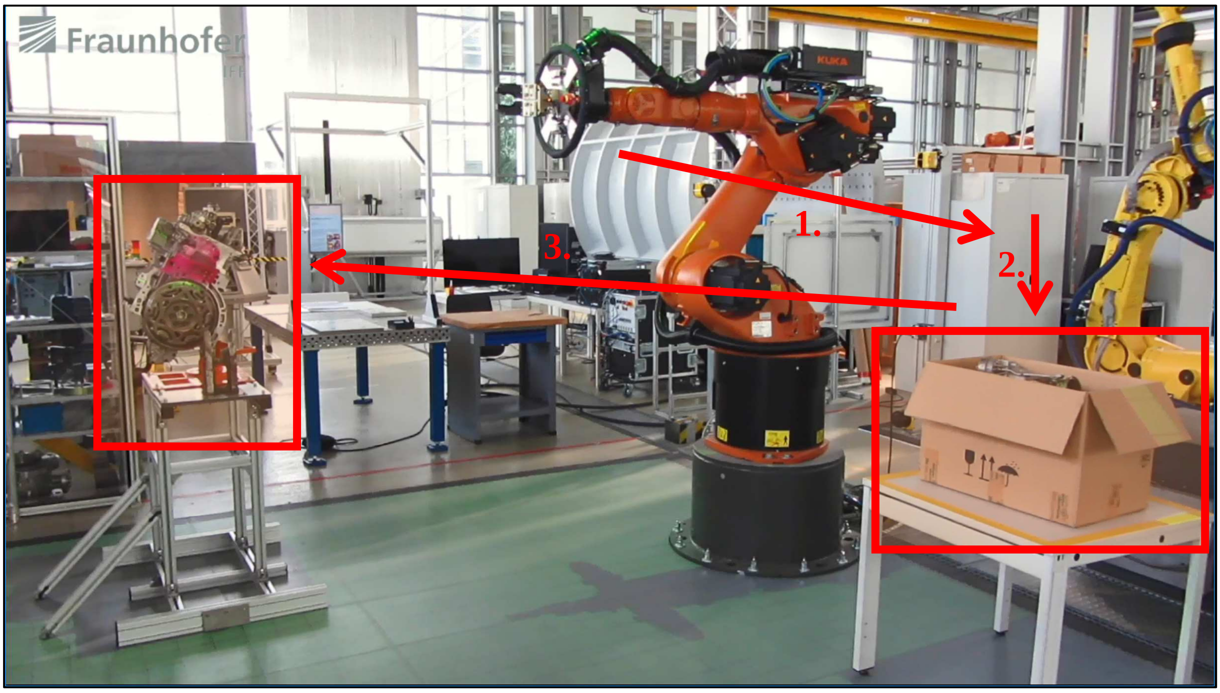


Figure 7: Single steps of the assembly process: Mounting a turbocharger to motor block.

3 Components integration and calibration

For using the hardware and software components in terms of a novel safety concept we need to integrate them into an entire working system. A schematic overview of relevant hardware and software interfaces can be seen in the following figure. The single software services for (i) acquiring the sensor data of the tactile floor, (ii) acquiring the robot's state data and (iii) providing the image data to the projectors are composed to an entire working software system. All interfaces between hardware and software components were established. The communication between robot and sensor system was implemented by using the KUKA RSI (RobotSensorInterface) interface.

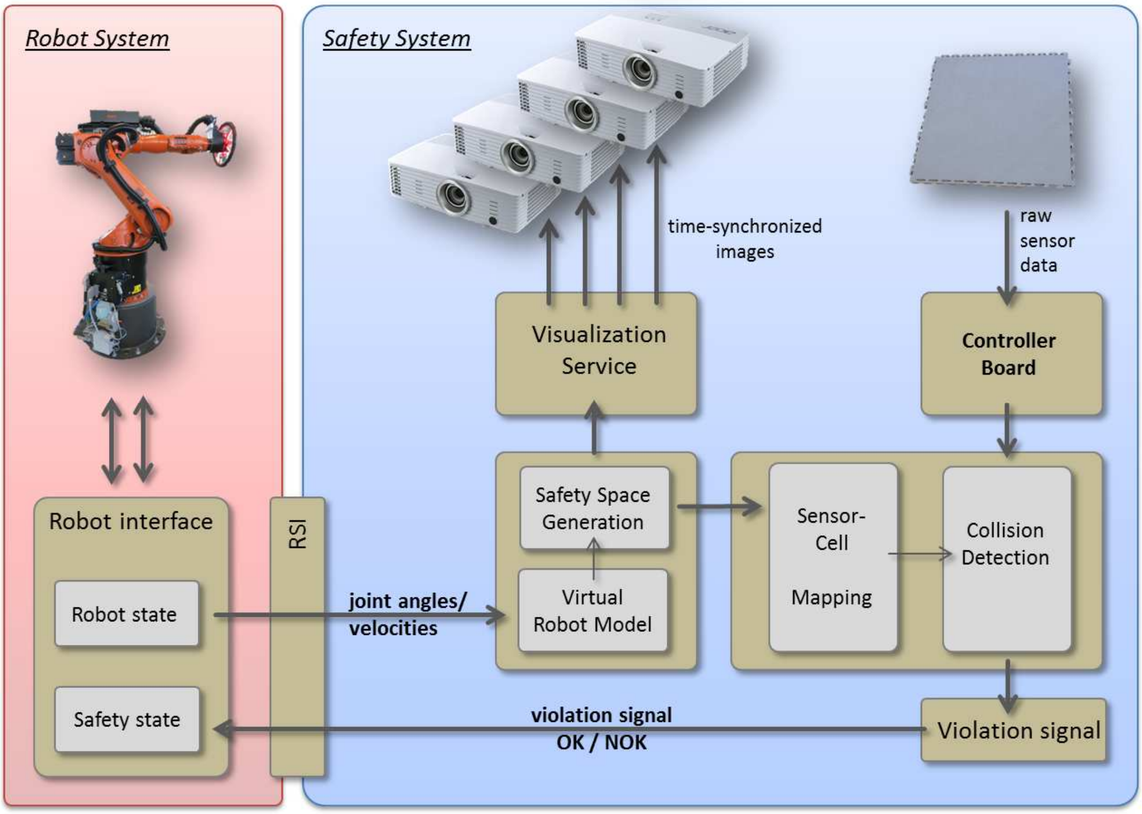


Figure 8: Overall scheme of the safety concept representing the main communication interfaces of software and hardware components.

After integration, the calibration of all hardware components that comprises the tactile floor, robot and projection system to a common coordinate frame is required. Here, the intrinsic and extrinsic calibrations of the projectors were of special interest. For that we developed and implemented a particular robot task to support the entire calibration process (see figure 9). For the intrinsic calibration we mounted the projector at the TCP of the robot and positioned them at about 20 different perspectives. For this we implemented a specific robot program. The projector visualizes a calibration pattern (i.e. circle pattern) on the flooring that was recognized by a pre-calibrated high-resolution camera. An optimization algorithm uses the 3D- object points and corresponding 2D- image points of the projected circles to estimate the intrinsic parameters of the projector.

After mounting the projectors at the system carrier we adjusted them to illuminate the entire human-robot workplace i.e. the entire surface of the tactile floor. For the extrinsic calibration we also use a pre-calibrated high-resolution camera to extract the circles of the projected calibration pattern and estimate the positions of the projectors accordingly.

Figure 9: Robot equipped with projector for intrinsic projector calibration. The projector is positioned at arbitrary perspectives.

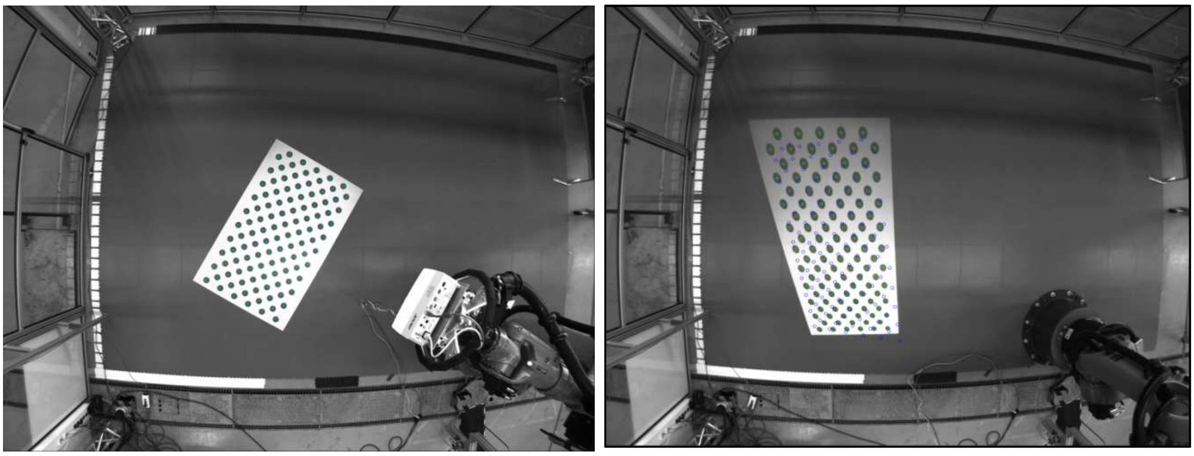


Figure 10: Projected calibration pattern from perspective of high-resolution camera. Circle detection for determining the intrinsic parameters of the projector.

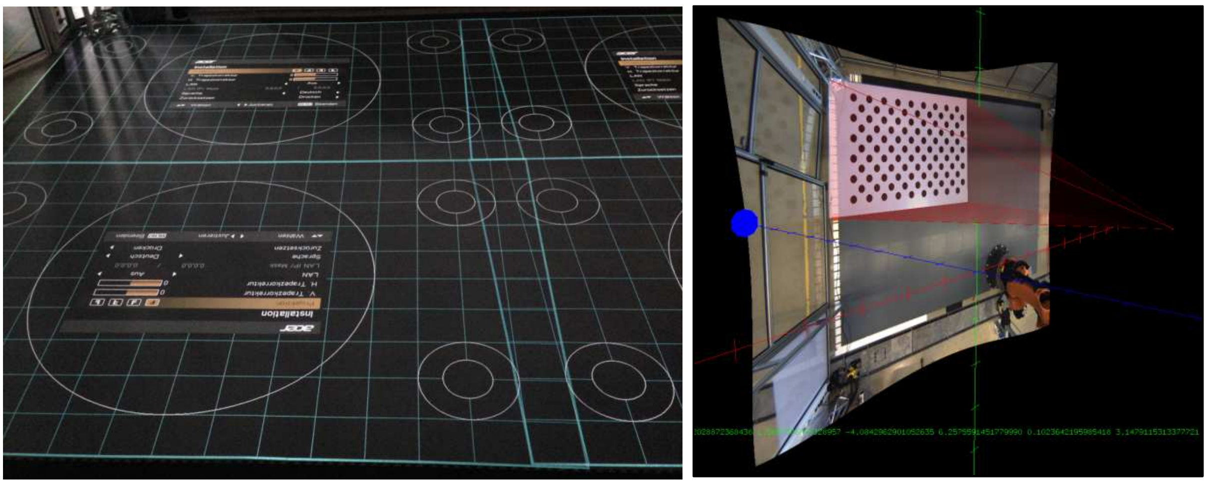


Figure 11: Extrinsic projector calibration. Left: Manual adjustment of the projectors. Right: Projection and detection of calibration pattern for optimizing the position by algorithms.

For visualizing an entire and seamless image at the surface of the tactile floor, we use the intrinsic and extrinsic parameters of every projector to warp and compose the single projector images. We further need to crop the images at overlapping image areas. This became necessary because the images appear brighter in neighboring areas at which the images overlap.

The robot as well as the tactile floor was calibrated concerning the common coordinate frame by means of manual measuring and transformation.

4 Estimation of human's behavior

The proposed safety concept aims in using the approach formula described in ISO/TS 15066 that enables the proposed safety system as an "speed and separation monitoring"- system. This approach formula considers also the movement direction and speed of the human. Knowing the human's behavior affects positively the calculated safety distance between human and robot (smaller safety distances). In this experiment, we aim on estimating the human's behavior on basis of the tactile floor's sensor data.

We implemented a prototypical method that estimates the movement direction and speed of one person on the tactile floor. Here, we developed a model-based approach to assume a movement of the human by detected steps. First of all, we need to detect the footprints of the human that normally consists of several triggered sensor cells of the tactile floor. We introduced so called "blobs" that consist of one or more individual triggered sensor cells activated by the human's foot. So, one blob consists only of such sensor cells that are spatially connected (i.e. neighbors). In the following figure you can see a blob that consists of 3 sensor cells (left) and 2 sensor cells (right).

Figure 12: Human's footprint consisting of different amount of activated sensor cells. Left: 3 activated sensor cells. Right: 2 activated sensor cells.

Further on, we try to correlate the blobs over time to detect a human's steps. If the human starts walking on the tactile floor, the blob of one footprint disappear (human raises foot) and appear on a new position (foot hit floor) afterwards. We can assume that the human has made a step. But this is not certain in all cases. The human can also interrupt the step and remains standing on one foot. In general, with the current implementation we can estimate the human's behavior robust when the human has done two steps. On basis of two steps, we can approximate the movement direction and speed of the human. In the following pictures you can see a typical sequence of a human's step on the tactile floor.

Figure 13: Typical sequence of a human's step on the tactile floor.

The human stands on one foot and moves the other foot to the front (figure 13, left). Only one blob is active but may vary at the amount of activated sensor cells. Next, the front foot hits the ground and activates further sensor cells that form another blob (figure 13, middle). Further on, the back foot raises and only the front foot blob is further active (figure 13, right). The back foot moves to the front and the sequence starts again with figure 13, left image. If we recognize such a sequence we assume that the human made a step. For estimating the movement velocity and direction of the human we consider the position and point of time of doing a step. This is the middle part of the step sequence (figure 13, middle) when both foots are on the ground.

We further evaluated the determined position and velocity by an external tracking system. Here, we used our optical marker-based position detection.

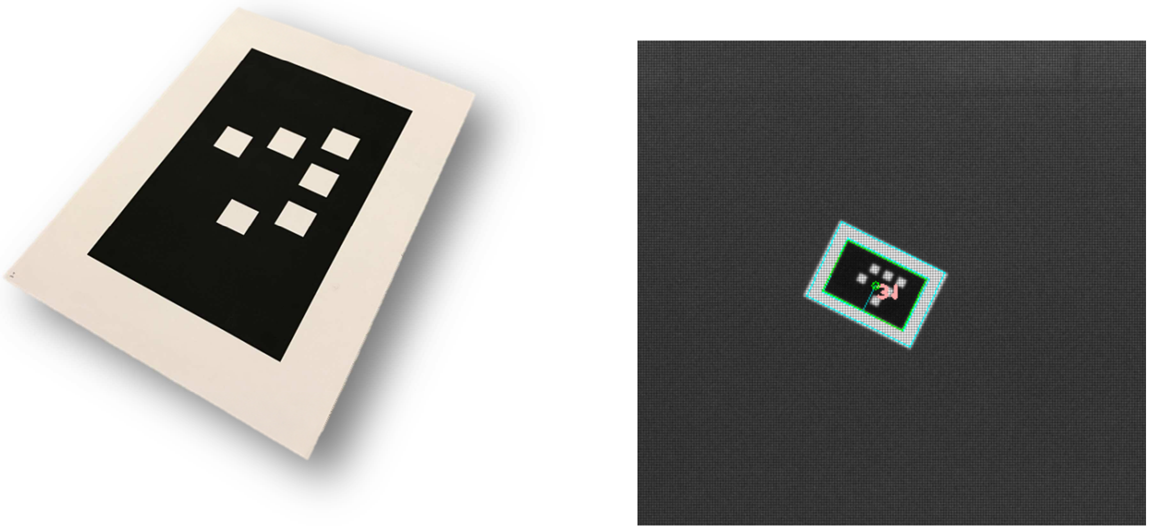


Figure 14: Marker detection for measuring the position and velocity of the human.

For validating the implemented algorithms to estimate the human's position and velocity by the tactile floor we used our marker-based tracking system. We further compared the results of the tactile floor with the results of the tracking system. In the following diagrams you can see on the one hand the estimated position and velocity of the tactile floor and on the other hand the determined position and velocity of the tracking system.

In the following diagrams we present the results of determining the Cartesian position of the human in x- and y- direction. For this, a person moved onto the floor while the system measured and logged the determined position. Here, we have x (red) and y (blue) of the tactile floor and x (black) and y (purple) of the tracking system.

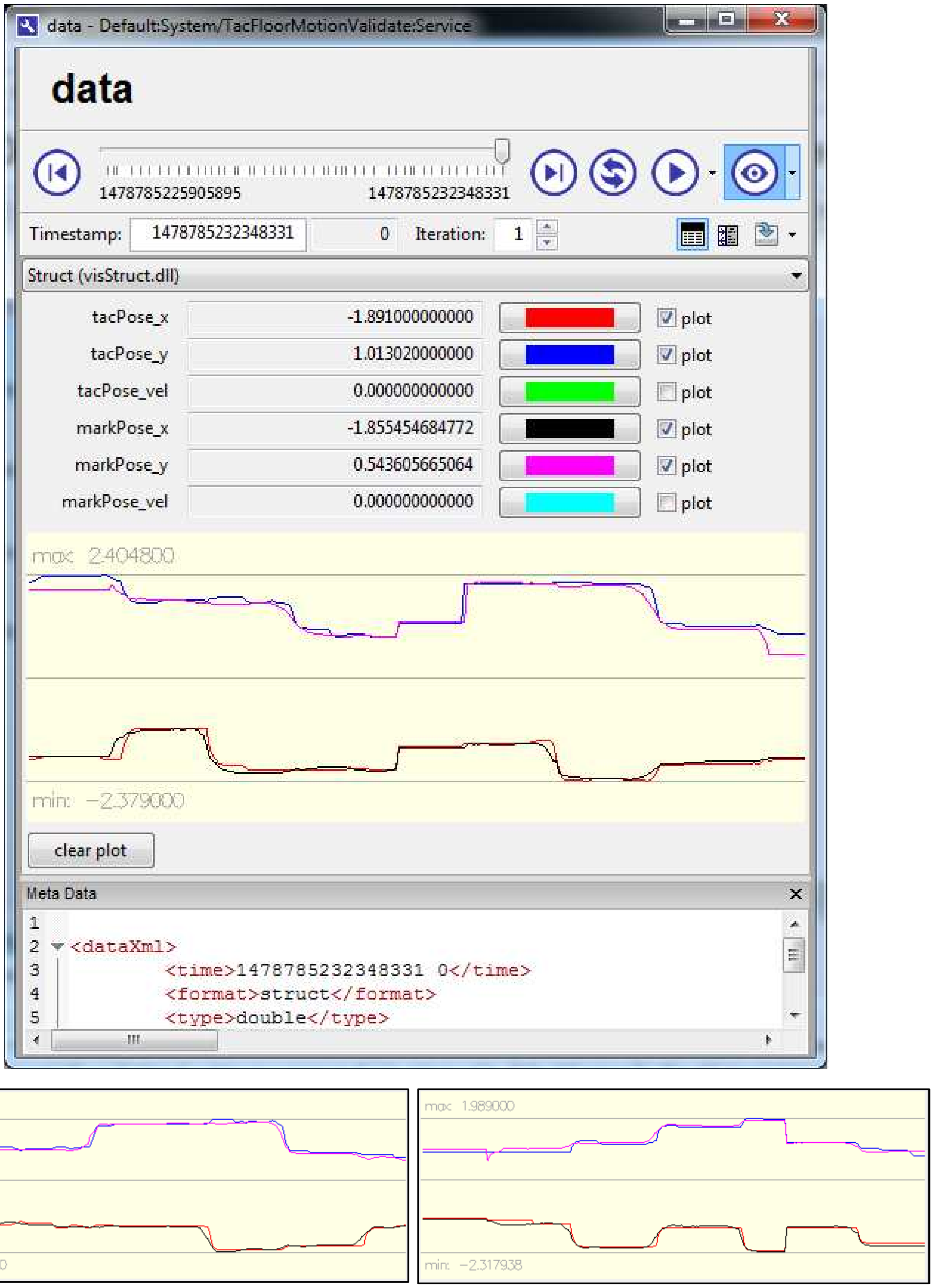


Figure 15: Comparison of human's position determined by tactile floor and tracking system.

It can be seen that the point of time the position changes is nearly synchronous. The deviations are in the limits as you consider the resolution of the tactile floor.

In the following diagrams we present the results of estimating the human's velocity. For this, a person moved onto the floor while the system measured and logged the determined velocity. For a sufficient comparison we tried to move along a straight path with constant velocity. For this we had only about 4 meters in length. So, the acquired data is only for a short time span. The calculated velocity of the human by the tactile floor is depicted green; the velocity of the tracking system is light blue.

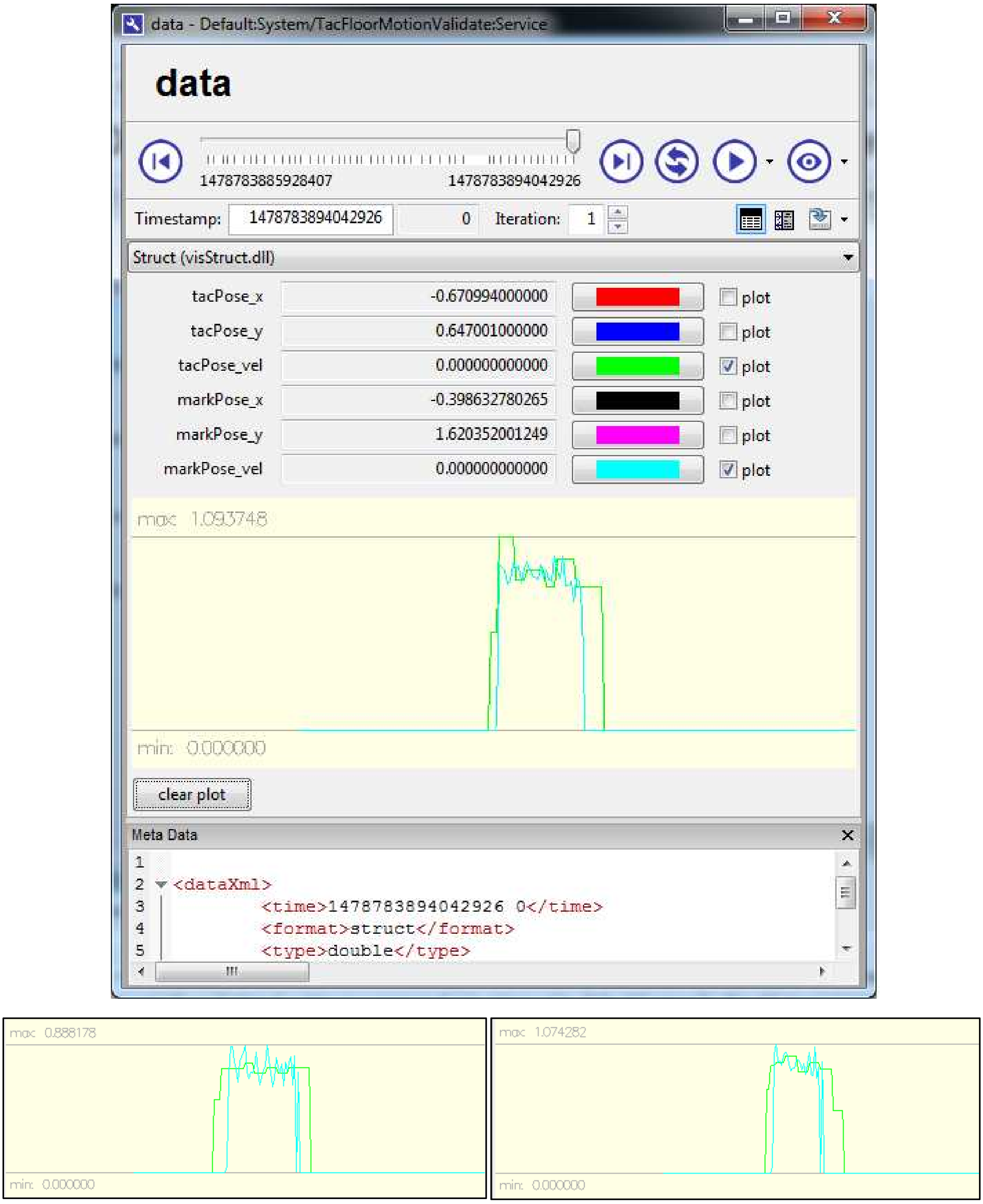


Figure 16: Comparison of human's velocity determined by tactile floor and tracking system.

The velocity of the tracking system is very noisy because of the low frequency of the measured marker positions. But it can be seen that the velocities are converging to a similar result.

5 Generation of safety spaces

The SAPARO experiment aims on introducing a novel safety concept that will lead to a step-change in human-robot cooperative scenarios with high-payload robots. The combination of a tactile floor and a visualization system provides safety, interaction and worker assistance. As we generate dynamically the safety spaces that need to be monitored, most of the human-robot shared workspace can be entered by the human without any risks thus providing a high degree of flexibility. The basis for this forms the approach formula that is described in ISO/TS 15066. The proposed safety concept implements this approach formula and enables the safety system to act as a "speed and separation monitoring" – system. Besides using the current joint positions and velocities of the robot, the safety system additionally incorporates the human's behavior. Knowing the human's movement direction and speed will result in smaller safety distances between human and robot. The implementation of this safety approach for determining dynamically the corresponding safety spaces is a main aspect of the SAPARO experiment.

A safety space is specified by a shape, size, pose and can be defined either manually or dynamically via algorithms. The focus is on implementing algorithms to generate dynamically safety spaces on basis of the current joint angles and velocities of the robot as well as the current behavior of the human. For developing the algorithms that compute the safety distances on basis of the approach formula specified in standard ISO/TS 15066, we implemented a simulation environment that allows the visualization and evaluation of the results as well as the convenient development and improvement of the algorithms (figure 17).

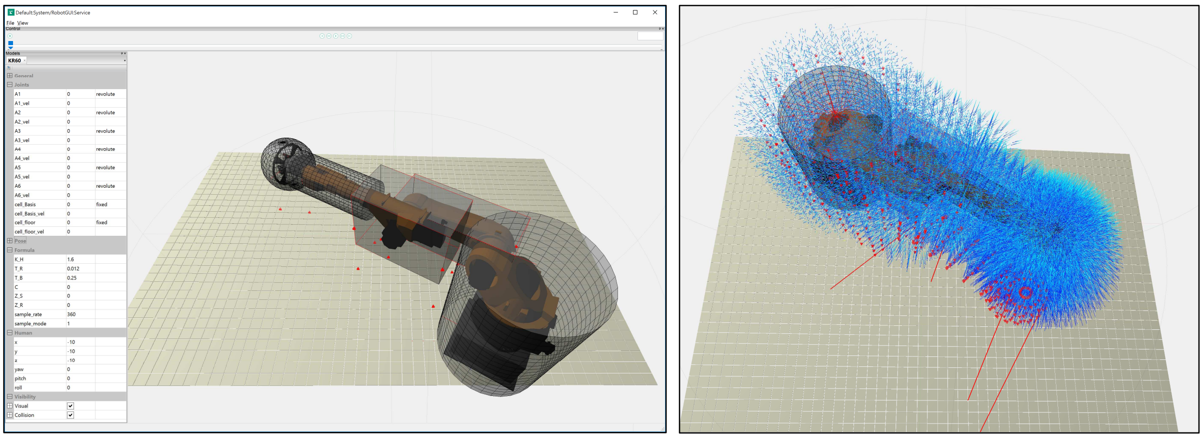


Figure 17: Simulation environment used to develop and implement the single safety approaches that are based on the distance formula described in ISO TS 15066. Right: Resulting safety distances (blue) at robot movement by a joint (A1) velocity of 0.8 rad/s.

This tool allows to load an URDF- described robot (and environment) and to visualize its geometry as well as the corresponding defined collision primitives (see figure 11, left). The position and velocity of every joint can be adjusted manually and is visualized accordingly. Beside the robot-related adjustments the user can also define the parameters of the approach formula like brake distance, reaction time and safety constants. It is also possible to define a human's position, movement direction and speed. At this point we are able to simulate all input parameters that are needed to calculate the safety distances between human and robot.

Actually, the safety distances have to be calculated for every single point of robot's surface geometry. That is a very complex and extensive issue. For reducing this computing complexity the robot's geometry was approximated by particular collision primitives. Further on, these collision primitives are sampled by a predefined sample rate to determine a set of surface points that are used to compute the corresponding safety distances. So, for every sampled surface point we compute the safety distance vectors in all possible directions resulting in a set of vectors representing the direction and safety distance. As the further processing of the entire set of 3-dimensional distance vectors was too challenging because of its quantity, we implemented a voxel-based structure (Octree) that allows the reduction of data and provides a more convenient handling and processing of the data.

The octree can be further used to determine a 3-dimensional convex hull that can be seen as a 3-dimensional safety space enclosing the robot. In the SAPARO experiment we just need a 2-dimensional representation of the safety space that needs to be monitored by the tactile floor. By using the calibration transformations of the robot and tactile floor we transform the safety distances and determine the corresponding sensor cells of the tactile floor. These 'critical' sensor cells were further processed to calculate additional 'warn' cells that surround them. As the robot reduces its motion speed while a human enters the 'warn' cells, the robot stops immediately at a triggered 'critical' cell. All other 'free' cells will not affect the robot's behavior.

5.1 Safety approaches

The SAPARO experiment aimed on developing and comparing different safety approaches that can be used to safeguard the human in human-robot shared workplaces with high payload robots. So, we defined the following safety approaches:

1. Fence guard and safety laser scanner:
   This is a traditional safety approach and represents the current state of the technique used in industrial automation to prevent humans from collisions with robots. If the human enters the shared workspace by opening the door or crossing the laser scanner's area the robot performs a safety-rated monitored stop. While the human is inside the shared workspace a movement of the robot is not permitted.

In the following safety approaches we use the tactile floor to monitor the safety distances between human and robot. The generation of the safety distances and resulting safety zones is different in every safety approach and is briefly described in the following. For calculating the safety distances (safety zones) we use the approach formula described in ISO/TS 15066.

2. Tactile floor: Semi-Static on basis of planned trajectory:
   The safety zone is defined on basis of the planned trajectory of the robot and remains static while the robot moves along this trajectory. The resulting safety zone is based on the robot's joint angles and velocities used while moving along the trajectory. So, the safety zone covers the entire area of the robot's movement alongside the trajectory.

3. Tactile floor: Dynamic on basis of current robot state:
   This dynamic safety approach generates the safety zone online while the robot is in motion. In more detail, the current robot's joint positions and velocities are used to generate a safety zone that encloses the robot minimally at any point of time.

4. Tactile floor: Dynamic on basis of current robot state and human behavior:
   In the SAPARO experiment we proposed this safety approach for generating safety zones. Besides incorporating the current robot's joint angles and velocities as described in approach 3, we additionally include the current human's movement direction and speed. On basis of this the safety system acts as a speed and monitoring system.

5.2 Evaluation of safety approaches

The comparison of the different safety approaches was done by a manually defined robot trajectory. As seen in the following figure we have a start position [1], an intermediate position [2] and target position [3]. So, the robot firstly moves from position [1] to position [2] and further on to the target position [3]. This trajectory will be used to evaluate the different safety approaches.

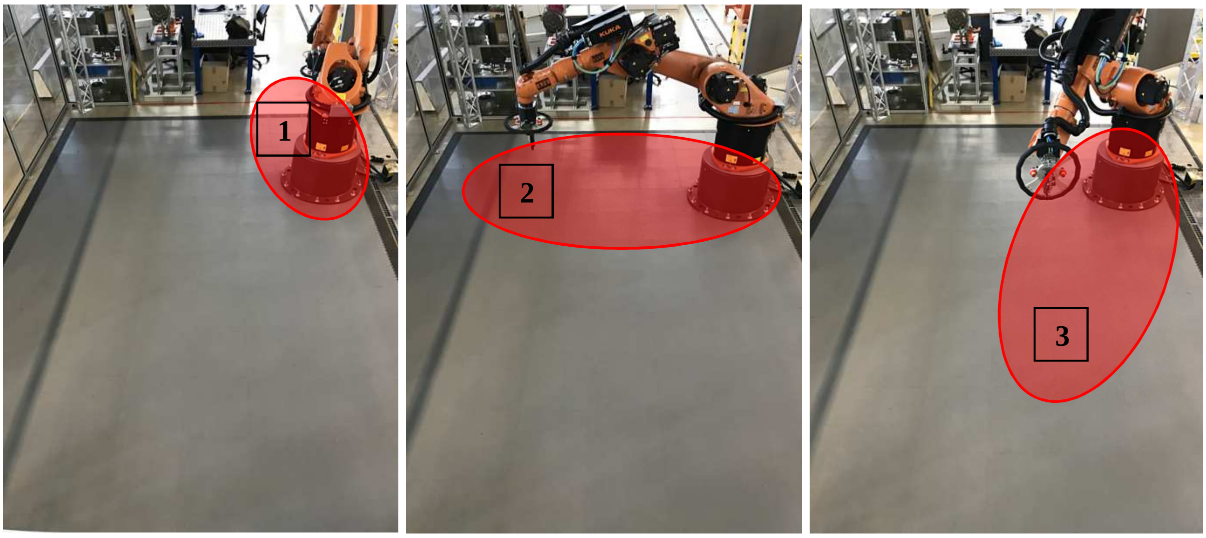


Figure 18: Pre-defined robot trajectory for evaluating the different safety approaches. Robot moves from initial position [1] via intermediate position [2] to the target position [3].

The robot moves along this trajectory while the movement was monitored by safety zones according to the different safety approaches. The main criterion for rating the safety approaches is:

- ***Free/usable area of shared workspace:***
  The free area of the shared workspace can be safely entered by the human while the robot is in motion. The size of this area can be used to evaluate the quality of the implemented safety approaches. More free/ usable area implicates a minimal dimension of the safety zone that encloses the robot and leads to an improved flexibility and ergonomic for the user.

This criterion may also influence the **cycle time of the overall process** and the **maximal robot speed**.

- ***Cycle time of overall process:***
  Smaller dimensions of the safety zones offer closer proximities between human and robot. Depending on the application this fact will allow higher cycle times of the process as the human has more flexibility and liberty to work. In fact, smaller dimensions will NOT negatively affect the cycle time of the process.

- ***Maximal robot speed:***
  Smaller dimensions of the safety zones offer the possibilities of higher robot velocities. We assume that the human has a constant distance between human and robot and this distance is bigger than the computed safety distance that was needed. So, there is more space between human and robot than necessary. In fact, the robot is allowed to increase its movement velocity while the current distance between human and robot is bigger than the calculated safety distance.

In the following we explain the application of the different safety approaches and the effects for the human-robot shared workspace.

1. Fence guard and safety laser scanner:
   As foreseen, this safety approach is not suitable for human-robot cooperative scenarios. A real cooperation between human and robot in the shared workspace is not possible. If the human enters the workspace the robot stops its motion and remains standing until the human leaves and confirms the leaving of the shared workspace. The simultaneous processing of tasks by human and robot is not possible.

   As the shared workplace is separated by fence and laser scanner there is no accessible/ free/usable area for the human. The entire area of the shared workspace is monitored. Therefore, the size of the free/usable area of the shared workspace that can be entered by the human is zero.

   ➔ *0 % of the shared workspace is free/usable for the worker.*

2. Tactile floor: Semi-Static on basis of planned trajectory:
   This safety approach allows a safe cooperation of human and robot in the shared workspace. The human can enter the shared workspace safely while the human is safeguarded by the tactile floor. The robot reduces its motion velocity when the human enters the warn area and will further stop its motion when the human enters the critical area.

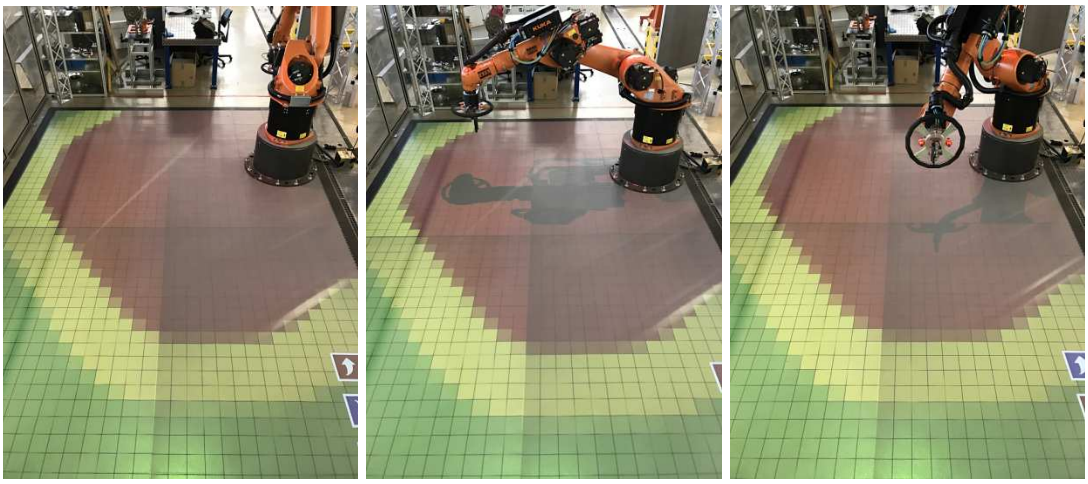


Figure 19: Movements of the robot monitored by semi-static established safety zones.

The resulting size of the semi-static safety zone depends only on the planned trajectory and its corresponding robot movements. In figure 19 the robot positions of the pre-defined trajectory are depicted. It can be seen that the safety zones are static at the entire movement of the robot.

In our scenario the effective free/usable area is small because of the extensive robot movements along the defined trajectory.

In figure 20 the total amount of sensor cells that belong to a critical zone or warn zone is depicted. As the safety zone is initially determined and does not change over time the total amount of sensor cells is static.

1245 sensor cells from a total of 1536 sensor cells belong to critical zone or warn zone.

➔ *About 19 % of the shared workspace is free/usable for the worker.*

3. <u>Tactile floor: Dynamic on basis of current robot state</u>
The dimension of the safety zone concerning this safety approach depends on the current robot's joint angles and velocities. The human's behavior is not considered. Regarding the approach formula the human's speed and direction is assumed as worst case. Here, it is assumed that the human moves straight forward to the robot with a velocity of 1.6 m/s. This safety approach is depicted in the following figure. It can be seen that the safety zones depend on the current robot's joint angles and velocities. The safety zones enclose the robot at any time.

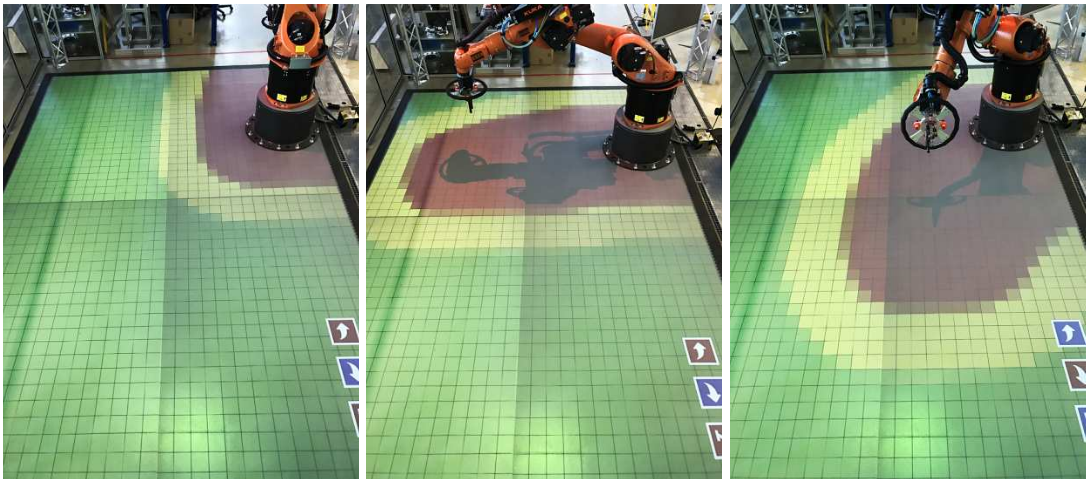


Figure 20: Dynamic safety zones on basis of current robot's joint angles and velocities at different robot positions. Amount of sensor cells: Left: 524; Middle: 924; Right: 967

The amount of sensor cells that belong to the critical zones or warn zones change while the robot moves. How many sensor cells are marked as critical or warn can be seen in the following figure.
In position [1] the safety zone covers an area of 524 sensor cells. At the movement from position [1] to intermediate position [2] the amount changes to 924 sensor cells. While moving from intermediate position [2] to target position [3] the amount changes to about 730 sensor cells and it reaches finally a total amount of sensor cells of 967.

➔ *About 66 % to 40% of the shared workspace is free/usable for the worker.*

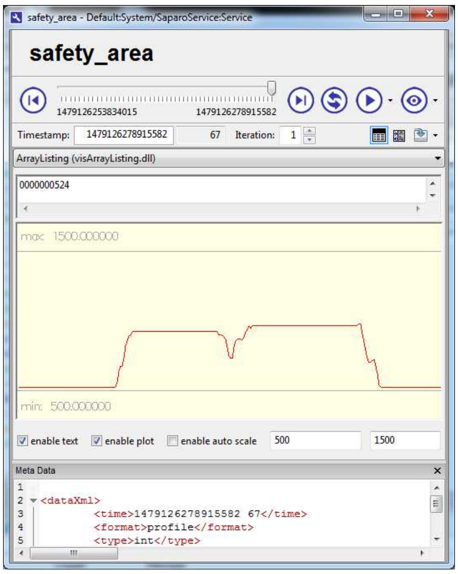


Figure 21: Safety approach 3: Amount of sensor cells that represent critical zone and warn zone while the robot moves from initial position [1] via intermediate position [2] to target position [3].

4. <u>Tactile floor: Dynamic on basis of current robot state and human behavior</u>
   In this safety approach the human's behavior is additionally incorporated to determine the dimension of the safety zone. As depicted in figure 23, the safety zones are enclosing the robot minimally at any time. While a human is moving in the shared workspace the human's position and movement direction is incorporated to safety zone generation. The width of the extension depends on the human's movement direction and speed.

   We further evaluated the influence of human's behaviour to the dimension of the safety zones. As seen in the figure 25 a person is moving straight forward to the robot. While moving the safety zones dynamically adapt the dimensions. In figure 26, the change of the amount of sensor cells that belong to the critical and warn zone can be seen clearly.

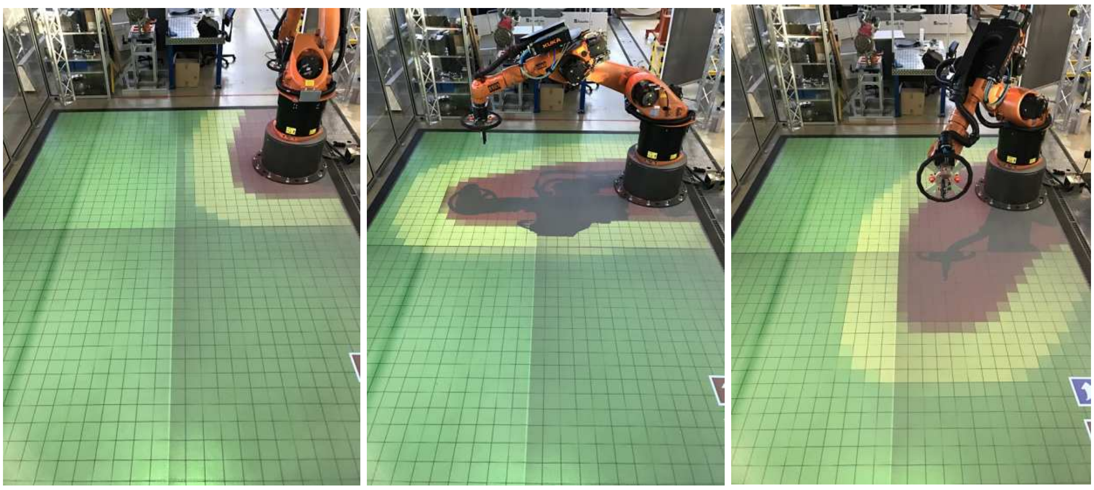


Figure 22: Dynamic safety zones on basis of current robot's behaviour and current human's behaviour. Amount of sensor cells: Left: 397; Middle: 739; Right: 723

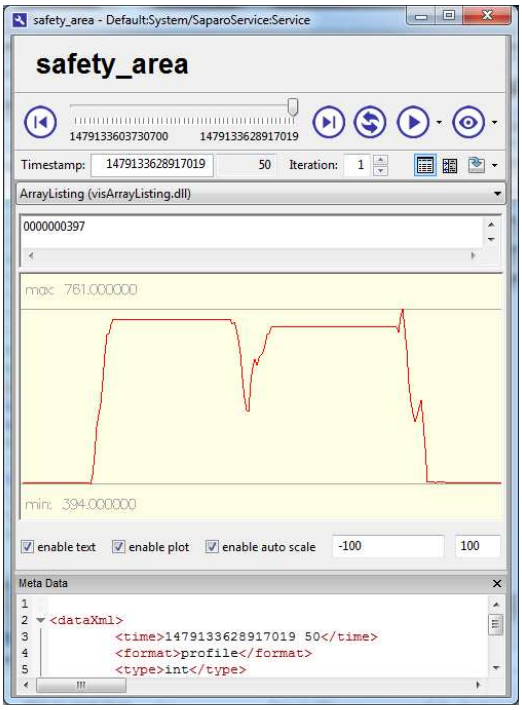


Figure 23: Safety approach 4: Amount of sensor cells that represent critical zone and warn zone while the robot moves from initial position [1] via intermediate position [2] to target position [3].

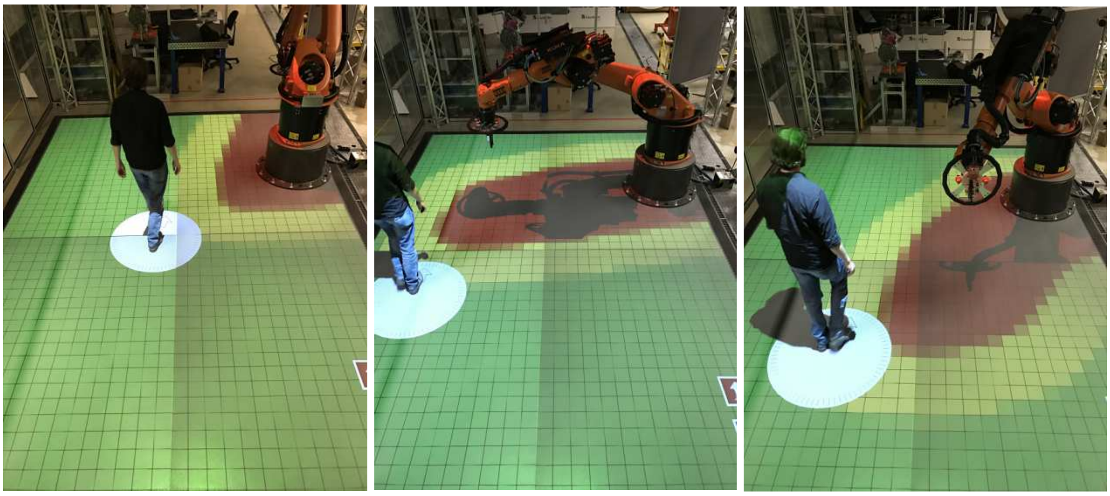


Figure 24: Human is moving straight forward to the robot while the dimension of the safety zones is adapted dynamically on basis of the human's behaviour. Left: Robot is in initial position [1]. Middle: robot is in intermediate position [2]. Right: robot is in target position [2].

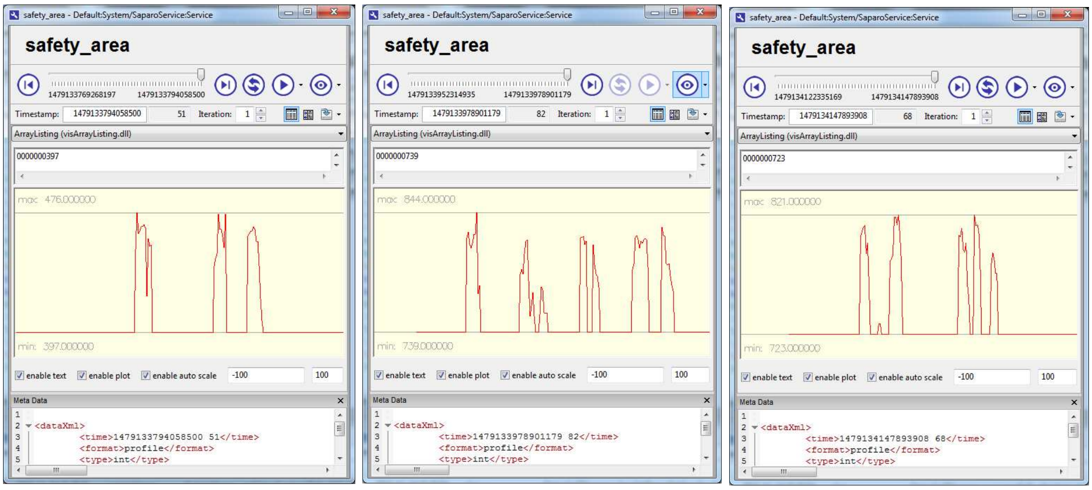


Figure 25: Change of amount of sensor cells that belong to critical and warn zone while a human is moving straight forward to the robot. The diagrams (left, middle, right) correspond to the single pictures in figure 25.

It can be seen that the safety zones enlarge in direction of the human by an area of about 1.5 m² (~ 100 sensor cells).

In summary, as expected the safety approach 4 offers the smallest dimensions of the safety zones. In general, having very small safety zones with no person is in the near of the robot makes no sense. Here, the small safety zone can lead to an increased velocity of the robot.

6 Visualization and interaction

The projection system implements the soft-safety aspect of the safety concept. The objective of this technology is the visualization of safety-specific, robot-specific and process-specific information that will lead to an improved ergonomics, user acceptance and robot availability. The projection system supports the user by visualizing useful and beneficial information directly into the workspace of the human. Here, the visualization of the current active safety zones is of utmost importance. The user is aware of the current dimension of the safety zone and can actively avoid the entering of this area. Preventing unintended movements into the safety zones and thus avoiding a violation of the safety zones leads to an improved availability of the robot and result in an improved availability of the entire process.

Furthermore, the user is aware of the free and usable area of the workplace that allows more flexibility and as much as possible working space for the user. We firstly implemented a method for visualizing the position and size of the single sensor cells of the tactile floor for verifying the calibration of the tactile floor regarding the common world coordinate frame. As shown in the figure we visualized the sensor cells as an overall grid. This is also very beneficial for demonstrating and explaining the safety concept to guests from academia and industry.

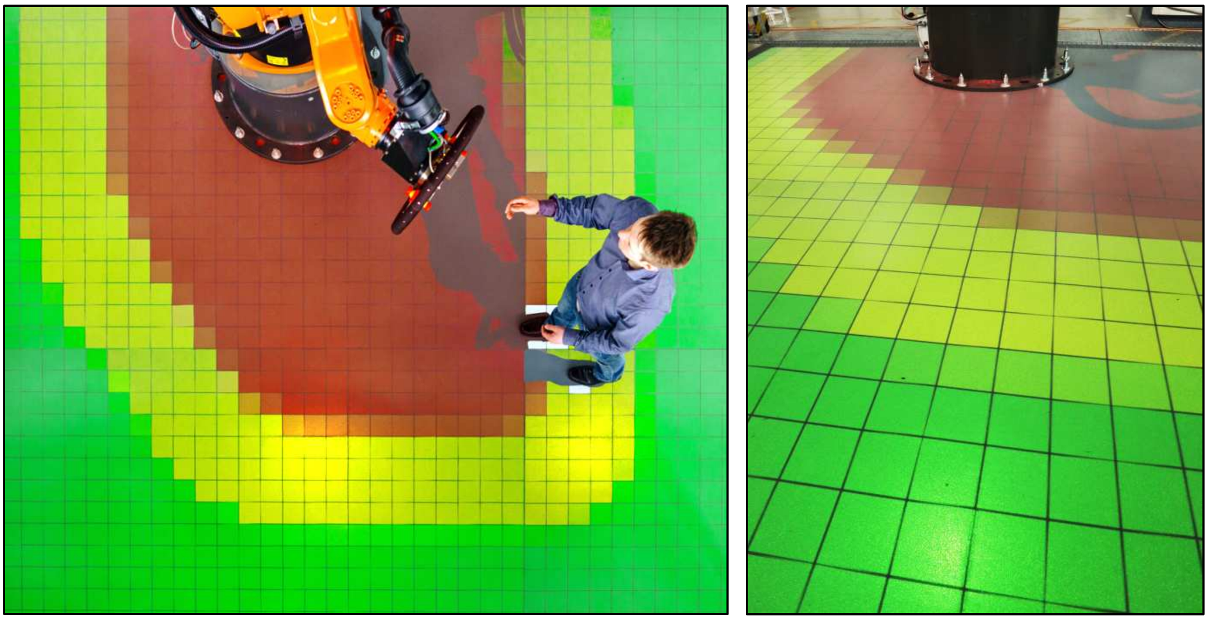


Figure 26: Grid-based representation of the sensor cells of the tactile floor. Dynamic generated safety zones that consist of a critical zone (red area), warn zone (yellow area) and free zone (green area).

So, the projection system visualizes the sensor cell grid of the tactile floor and represents the different safety zones by particular colors (green, yellow, red), as depicted in figure 27. Sensor cells that measured a contact are filled whitely.

Besides the visualization of the safety zone's dimension the visualization of next movement directions and robot's target position are further enhancements to improve the user's acceptance. We also implemented a text area that shows status messages of the process. This will also support the user in doing the work. In general, we can visualize any graphical representation, textual descriptions or schemes at certain positions in the workspace. In the following figure you can see the animated symbols for representing next robot's movement direction and target position.

Figure 27: Visualizing next robot's movement direction (left) and target position (right).

In figure 29 the implemented text area for visualizing arbitrary messages is depicted.

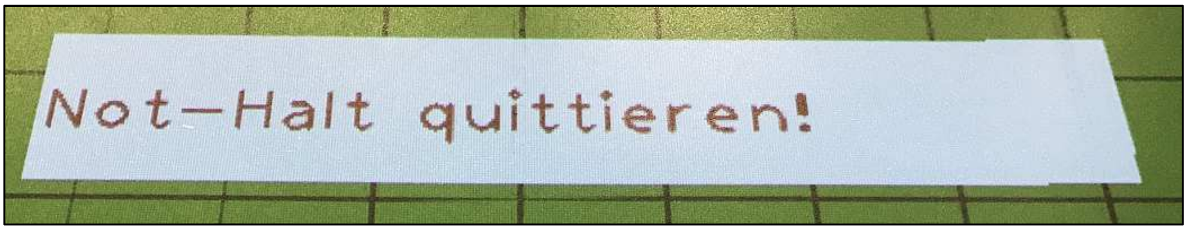


Figure 28: Text messages for specific user information.

We further use individual sensor cells for interacting with the system, process or robot. These sensor cells are marked by a particular symbol (see figure 30) and will release a specific functionality at a detected contact. So, the user simply needs to step onto the sensor cell that is marked by symbol to control the system, process or robot. We implemented exemplarily three interactive buttons for start specific movements of the robot and to enable/disable the robot's hand guidance.

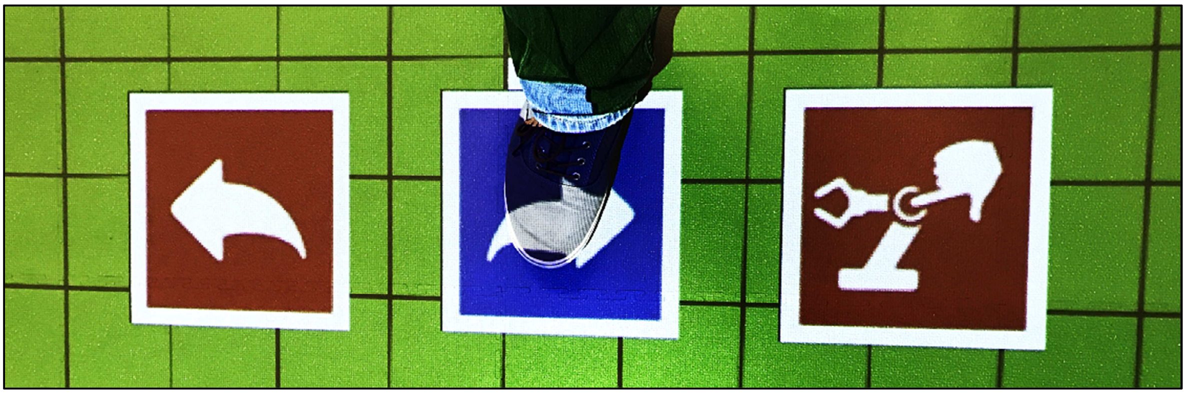


Figure 29: Interactive buttons to control the system, process or robot.

We further visualize the human's behavior by a white circle representing the estimated position as depicted in figure 31, left picture. While the human is moving on the tactile floor this movement is recognized by the system. The estimated movement direction is visualized as a red arrow pointing in human's movement direction (see figure 31, right).

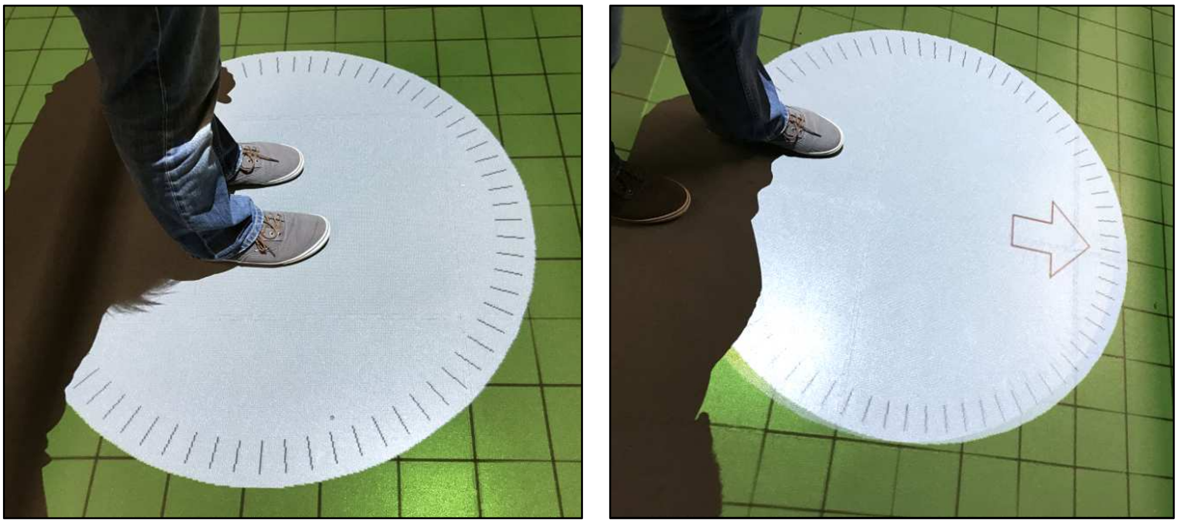


Figure 30: Visualization of detected human's position (left) and estimated movement direction (right).

The benefits and acceptance of the projection system was evaluated by a questionnaire. As foreseen, the user felt not safe if there is no visualization of the safety zones and next robot movements.