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

Deliverable 1.1 – System specifications/ requirements, Use-case descriptions, and Experimental plan

Authors:

Christian Vogel

Jochen Vetter

Name of the Coordinating Person:

Dr. Norbert Elkmann

Institution of the Coordinating Person:

Fraunhofer Institute for Factory Operation and Automation, Sandtorstrasse 22, 39106 Magdeburg, German

1 Introduction

Current industrial applications with human-robot collaboration focus on the use of 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.

In the SAPARO experiment we propose an innovative and trendsetting solution for safeguarding collaborative human-robot workplaces with high payload robots through a combination of safeguarding technologies addressing both hard[1]- and soft- safety[2] considerations. 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 the boundaries of the safety zones. We further develop and implement algorithm and software to dynamically define the safety zones around the robot depending on its actual movements (not static, pre-defined safety zones), which will be safeguarded by the tactile floor and visualized for the worker by the projection system. The safety zone will be generated online according to the relevant guidelines in EN ISO 13855 and will be based on the robot's joint angles and velocities. 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.

In this document we want to present the technical specification concerning the workplace with all the necessary hardware and software components. We further describe the scenario and use case, characterize the various safety approaches and present the experiments plan.

[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 Technical Specification

In this chapter we specify the technical requirements concerning the hardware and software components that comprise mainly the setup of the workplace with robot, system carrier and sensor system. These specifications comply with the requirements regarding the defined scenario and use-case presented in chapter 3.

2.1 Workplace setup

The shared workspace between human and robot covers an area of 4.0 by 6.0 meters. This area is sufficient to meet the requirements for implementing the defined scenario and use case. 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 workspace. The other two sides are fenceless (yellow-colored) and have to be safeguarded by safety laser scanner because of potential hazards by the robot. The entire shared workspace has to be equipped by the tactile floor to detect humans that approach the robot.

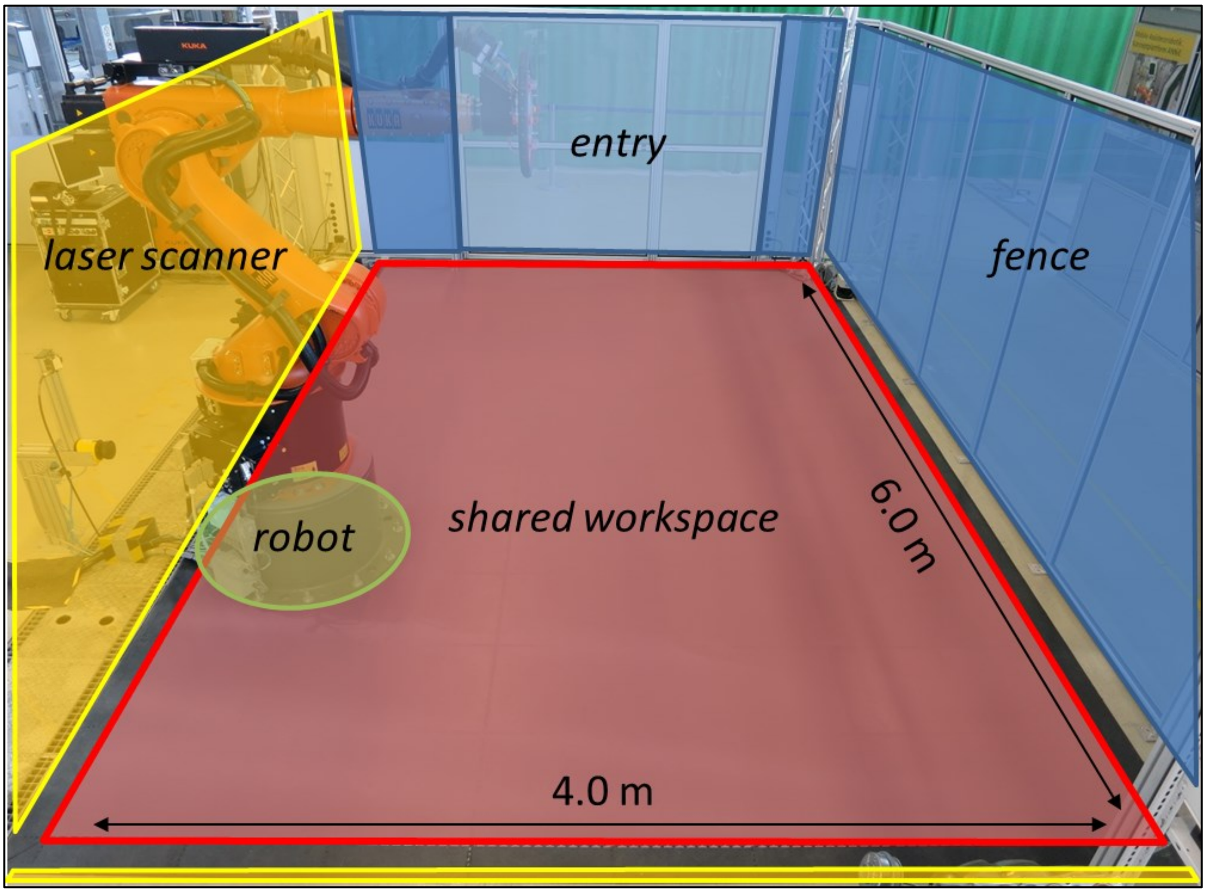

Figure 1: Entire workplace with shared human-robot workspace, robot and additional safeguarding by fences and laser scanner.

Beside the tactile floor the safety concept of the experiment comprises also a projection system to visualize safety space boundaries to the human. The necessary projectors have to be mounted above the shared workspace to allow an occlusion free perspective to the tactile floor. For this, a system carrier has to be build up that may be equipped by several projectors, as shown in figure 2. This system carrier is sized to an area of 6.50 by 5.00 meters. The height is limited to 4 meters because of structural constraints in the technical center.

Figure 2: System carrier for mounting the projectors.

2.2 Robot – KUKA KR60 L45

As the experiment aims in developing and implementing a novel safety concept for safeguarding the human in shared workspaces with high-payload robots, the robot used in our experiment should be sized accordingly. Here, we use a KUKA KR60 L45 that is able to handle 45 kg by a maximum range of 2.23 meters. This robot (see figure 3, left) is additionally equipped by a circular hand-guidance device (see figure 3, right) for an easy positioning of the robot's tool center point. This operator device will be used to manually fine position the grasped workpiece to the assembly counterpart. In the center of that operator device is the gripper system located, that is used to grasp objects up to 20 kilograms.

Figure 3: KUKA KR60 L45 with additional operator device and gripper.

2.3 Tactile Floor

The tactile floor is responsible for providing the hard safety functionality of the safety concept. This pressure sensitive sensor system has to cover the entire area (4.0 by 6.0 meters) of the shared work-space as visualized in figure 1.Humans moving on this area must be robustly detected to prevent them from collisions by the robot's motions. For this, the tactile floor is divided into several safety zones that lead to well-defined reactions due to triggered human detection. These safety zones will be differ-entiated in free zone, warn zone and critical zone. While the free zone can be accessed by the human safely, the entering of the warn zone will lead to a reduced motion speed of the robot and the robot will further stop its motion if humans enter the critical zone. These safety zones can be manually de-fined or even programmatically on basis of the current robot's joint angles and velocities. The tactile floor will provide these safety zones by selecting and labeling the corresponding single sensor cells located in the area of a particular safety zone. Here, the definition of an appropriate resolution of the tactile floor that implies the specification of the size of a single sensor cell is fundamental.

On basis of the experiences obtained by the Fraunhofer IFF regarding prior developments of pressure sensitive sensor systems and tactile floors, the size of a single sensor cell is specified to 0.125 by 0.125 meters. This dimension of a sensor cell is well-suited to robustly detect the footprints of humans. Therefore, the entire floor will comprise 1536 sensor cells that have to be managed by a controller board as depicted in figure 4. Such a board is responsible to acquire the sensor data of every single sensor cell and provides these data via USB to the computing hardware. This board provides addition-ally some sensor specific adjustments like the thresholding of the trigger signal of a sensor cell at de-tected contact. The sensor cells will be adjusted to robustly detect contacts at a minimum weight of 10 kilograms that is sufficient to detect humans.

Besides the safety aspect of the tactile floor this technology provides additional interaction capabili-ties. Here, single sensor cells can be configured to execute certain functionality at a detected contact.

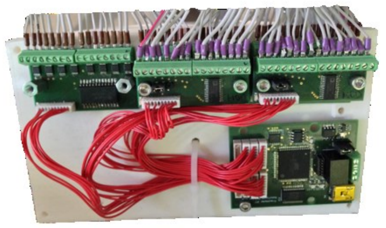

Figure 4: Controller board for managing the sensor cells.

The covering of the tactile floor is realized by industrial mats as depicted in figure 5. These mats have a size of 0.50 by 0.50 meters and are capable of bearing by heavy vehicles like pallet carriers to protect the sensitive sensor system underneath. To cover the entire shared workspace a total of 96 mats are necessary.

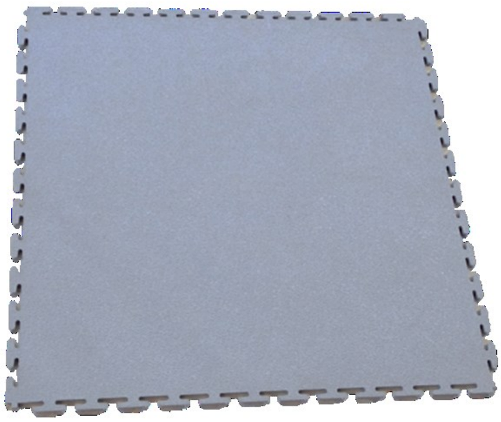

Figure 5: Covering of tactile floor consists of single industrial mats.

2.4 Projection system

The projection system states the second part of the safety concept proposed in this experiment. The aim of this system is to visualize on the one hand safety-relevant information and on the other hand additional beneficial information to the human. The safety-relevant information will mainly comprise the visualization of the different safety zones as well as hints regarding the robot's movement direction and target position. Further visualization will include some process and task relevant information like worker assistance. Here, the projection system will support the human by depicting schemes, images or textual descriptions of the current or even next steps of a task.

As described in section 2.1 the projectors shall be mounted on the system carrier in a height of maximal 4 meters. For illuminating the entire shared workspace of 4.0 by 6.0 meters a minimum of 4 projectors are necessary. Here, we identified a DLP projector that provides an aperture angle large enough to cover a minimal area of 2.0 by 3.0 meters thus offering the possibility to use 4 projectors in total. This projector (Acer P5327W, see figure 6) features a resolution of 1280 by 800 pixels and a luminous flux of 4000 lm. This is sufficient to project images with high resolutions and is further bright enough to see them despite additional external illumination.

Figure 6: Projector used to visualize safety-relevant and user information onto the tactile floor.

2.5 Hardware and software interfaces

In this section we describe the interconnection of the hardware components and data transfer. The following scheme depicts the overall workflow of the safety concept divided into two main parts, the "Robot System" and "Safety System". As the experiment uses a KUKA robot the communication between the two parts is done by RSI (Robot Sensor Interface). Currently, a safe communication to the robot for acquiring the robot's joint angles and velocities is not available. These data is used to update the internal virtual robot model that forms the basis for the following safety space generation algorithms. The generated safety space configuration is further used by the visualization service to display an appropriate representation. Besides this, the safety space configuration is mapped to the single sensor cells of the tactile floor that are further used for collision detection. Here, the current sensor data is checked regarding safety space violations. A safety space violation is signaled if a triggered sensor cell is located in the area of a safety zone. This signal will result in a reduced motion speed or entire motion stop of the robot.

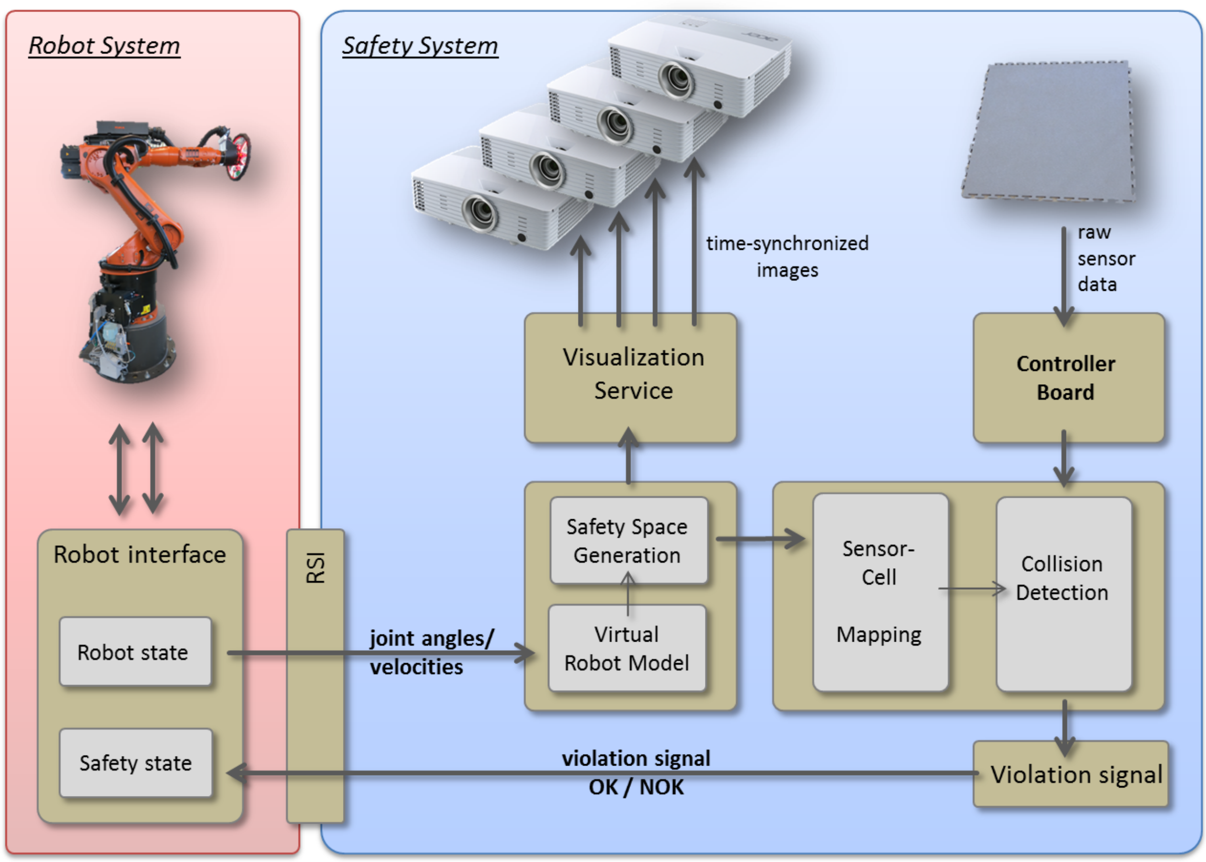

Figure 7: Overall scheme of the safety system representing the main parts of software and hardware components

3 Scenario and Use-case description

3.1 Description of Industry-oriented process

The aim of the SAPARO experiment is the development and evaluation of a novel safety concept for safeguarding human-robot cooperative tasks with high payload robots. To demonstrate the intended application and industrial relevance we implement a real industrial process. In our scenario the robot is used as a workpiece carrier for autonomously grasping, transporting and positioning heavy workpieces for the user. The usage of a robot as a workpiece carrier for easy and optimal positioning workpieces for the user is a relevant human-robot cooperation scenario in industry.

In detail we implement an assembly scenario in the domain of automotive industry. The relevant process comprises the mounting of a turbocharger to the related motor block. The robot supports this process by carrying the heavy turbocharger while the human tightens the turbocharger to the motor block. The single steps of this scenario are explained in detail in the following section.

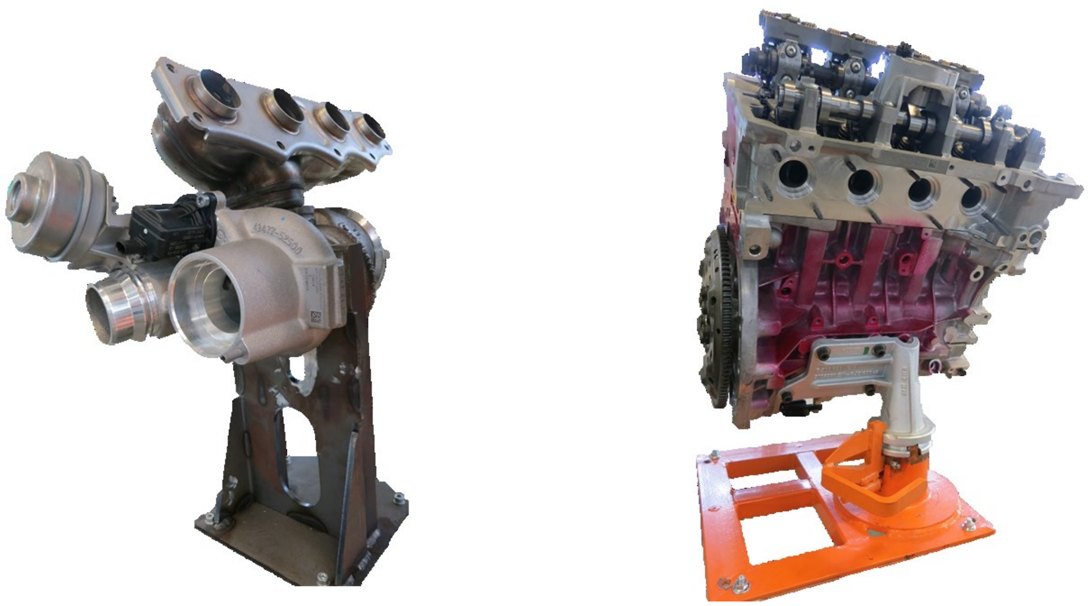

Figure 8: Assembly of turbocharger (left) and motor block (right).

3.2 Description of Use-case

As the industry-oriented process aims in supporting the human in transportation and handling of heavy objects, the use case of the scenario is the manually assembly of a turbocharger and motor block. Firstly, the robot needs to grasp the turbocharger from the workpiece supporter station that is located at a predefined position in the robot's working area. Further, the robot transports the turbocharger to the human's assembly station fully autonomously. This task needs to be monitored by the tactile floor to safeguard the human from collisions with the robot. When the turbocharger is positioned the human will adjust the turbocharger to the motor block by hand-guidance. This is done by the circular operator device at the TCP of the robot. Further on, the turbocharger is tightened to the motor block and the hand-guided robot is moved away. After that, the human confirms the end of this task and the robot starts moving back to its initial position autonomously. Here, the robot's motion is again monitored by the tactile floor.

Summary of main tasks of the use case:

1. Robot grasps turbocharger from workpiece supporter
2. Robot transports turbocharger to human's working position
3. Hand-guided robot adjusts turbocharger to the motor block
4. User manually tightens turbocharger to the motor block
5. Confirmation of task end and autonomous robot motion to initial position

The use case comprises three tasks (1, 2 and 5) that are safety relevant because of the autonomous motion of the robot and thus need a safeguarding of the human. In this experiment we propose a novel safety concept comprising a tactile floor and projection system to monitor the robot's motion. In detail, the sensor system may establish different kinds of safety zones that will be of static or dynamic manner. In the next section the different types of safety approaches are explained in more detail.

4 Safety approaches

The scenario described in section 3 is a typical human-robot cooperation scenario in industry that need appropriate safeguarding in operation. The proposed novel safety concept provides a tactile floor that is responsible to robustly detect humans in the shared workspace. If a human is detected in close proximity to the robot, the robot's motion speed has to be reduced or entirely stopped. The safety distance between human and robot is represented by safety zones enclosing the robot entirely. Here, we differentiate between free area, warn area and critical area. While the free area can be entered safely by a human, the access of the warn area will lead to a reduced motion speed of the robot that will further stop its motion if a human enters the critical area. The generation of these safety spaces can be done either manually or programmatically. The manual definition results in static safety spaces which don't change its size, shape or position in operation. The programmatic definition leads to dynamic safety spaces that will be generated online at operation. For dynamically generating safety spaces it exist several approaches that will be presented in the following. Besides the safeguarding by tactile floor we additionally list a safety concept that is currently established in automated processes and represents the state of the art in industry. This approach will be used as reference system for the evaluation and validation of the proposed safety concept.

4.1.1 Fence guard and safety laser scanner

This traditional safety system is currently established in industrial automation to prevent humans from collisions with robots. As seen in figure 1 the shared workspace is safeguarded by laser scanner and fences. If a human enters the shared workspace by opening the door or crossing the laser scanner the robot performs a safety-rated monitored stop. Therefore, a cooperation of human and robot in the same workspace is neither allowed nor possible.

In the SAPARO experiment this safety system is build up as a reference system to evaluate the proposed safety concept regarding advantages and drawbacks compared to the state of the art in industry.

4.1.2 Tactile floor: Semi-Static on basis of planned trajectory

This approach uses the planned trajectory of the robot to generate an appropriate safety space enclosing the entire area covered by the robot's motion along this trajectory. The resulting safety zone bases on the robot's joint angles and joint velocities used at robot's motion.

Before the robot starts its motion the generated safety spaces are established and monitored regarding the entering of humans. While the robot moves the safety spaces are static and don't change until the robot reaches its target position.

If it is not possible to acquire the robots' joint angles and velocities of a planned trajectory offline, we will record the used joint angles and velocities of an appropriate reference motion of the trajectory by the robot.

4.1.3 Tactile floor: Dynamic on basis of current robot state

This approach incorporates the current robot's joint angles and velocities at robot motion to generate a safety zone that encloses the robot minimally. In contrast to the semi-static approach the safety space is just based on the current robot's state and is generated online at any point of time. Therefore, the resulting safety space offers a wide area of the shared workspace to the human.

The method to generate the safety zones is based on the approach formula proposed in standard EN ISO 13855 and TS 15066. Here, the minimal safety distances between robot and human are determined.

4.1.4 Tactile floor: Dynamic on basis of current robot state and human behavior

This approach states the favored one that will be evaluated in the scope of the SAPARO experiment. Besides incorporating the current robot's joint angles and velocities as stated in the previous approach, this approach considers also the human's behavior. In detail, this concerns the human's movement direction and speed.

Here, it has to be evaluated whether the human's behavior affects the resulting size and shape of the generated safety space noticeably. The method to compute the safety spaces size, shape and position is based on the approach formula presented in TS 15066.

5 Experimental Plan

The experimental plan describes the method to evaluate the single safety approaches presented in section 4. The reference safety system is defined as approach 1 that represents the state of the art in industrial automation. The further approaches are evaluated concerning this reference system. In this section we will further present the test criteria as well as the test cases relevant for the evaluation process. The evaluation is done on basis of the specified scenario and use case in section 3.

In general, the experiment focus on the evaluation of a novel safety concept that provide a cooperation of human and robot in a shared workspace while maintaining its safety. For this, the size of the usable area as well as the time needed to execute the use case, are the main characteristics for the evaluation.

5.1 Evaluation criteria

The single safety approaches presented in section 4 are evaluated concerning the following test criteria. It will be in the responsibility of the experimenter to add, change or alter the evaluation criteria and test cases to provide as most as possible a significant and valuable outcome.

5.1.1 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 progress. This area is measured and the resulting value represents the quality of the safety space generation method concerning a minimal enclosure of the robot.

5.1.2 Cycle Time of overall process

The specified use case in section 3 is executed and the overall time is measured for every single safety approach. The time is a measure to the cooperative quality between human and robot monitored by a certain safety approach.

5.1.3 Maximal robot speed

The robot's speed depends on the distance between human and robot and may vary between the different safety approaches.

5.1.4 User awareness

As the safety spaces are visualized by the projection system the human may actively avoid a violation of them. A questionnaire is filled in by test persons to rate this assistance and support.

5.2 Test cases

The following test cases are elaborated to evaluate the single safety approaches. The test cases are executed while the robot is in motion.

5.2.1 Human stands outside the workspace

While the robot moves the human stands outside the shared workspace.

5.2.2 Human stands inside the workspace (free area)

The human stands inside the workspace but does not violate the safety space of the robot.

5.2.3 Human stands inside the workspace (warn area)

The human stands inside the workspace and affects the robot's motion by violating the warn area.

5.2.4 Human stands inside the workspace (critical area)

The human stands inside the workspace and affects the robot's motion by violating the critical area.

5.2.5 Human moves directly to robot's motion direction

The human moves directly to the robot's motion direction and will violate the safety zones.

5.2.6 Human moves perpendicular to robot's motion direction

The human moves perpendicular to the robot's motion direction and will violate the safety zones.

5.2.7 Human moves parallel to robot's motion direction

The human moves parallel to the robot's motion direction and will not violate the safety zones.