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

- SAPARO -

Fraunhofer IFF

Pilz GmbH & Co. KG

Final Report

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Section 1: Executive summary

- 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 beneficial information like the boundaries of the safety zones.
- We further develop and implement algorithms and software to dynamically define the safety zones around the robot depending on its actual movements, 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 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 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.

[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

Section 1.1: Milestone overview

#	Description	status
M1	Workplace and safety components (HW)	Timely achieved
M2	Integrated system	Timely achieved
M3	Experimental results	Achieved

Section 1.2: Deliverable overview

#	Description	status
SB	Story Board	submitted
D1.1	System specifications/requirements, Use-case descriptions, and Experimental plan	submitted
MMR1	Multi-Media Report	submitted
D4.1	Collaborative workspace hardware	submitted
MMR2	Multi-Media Report	submitted
D4.2	Working prototype	submitted
MMR3	Multi-Media Report	submitted
RIF	Report on RIF visit outcome	submitted
D7.1	Experimental results	submitted

RIF: The planned visit of the Bristol RIF was skipped because of the lack of both a high-payload robot and space (4.0 by 6.0 meters) needed by the experiment. The visit of the Paris RIF was also not possible, because of these reasons.

Section 1.3: Technical KPIs

#	Description	status
1	People reliable detection	Achieved
2	Efficient estimation of direction and speed of movement relative to the robot	Achieved
3	Gains in process integrity due to soft-safety components	Achieved
4	Ease-of-use of the tactile floor mat	Deviated
5	System efficacy	Achieved

4: It was planned to verify the ease-of-use by rebuilding the system at Bristol RIF. As the RIF visit was not possible we verified this point by using the experience from the initial buildup at our laboratory.

Section 1.4: Impact KPIs

#	Description	status
1	Providing a novel solution (safety concept) for safe coexistence and collaboration between humans and robots, especially addressing scenarios with high payload robots and large-scaled robot workspaces.	Achieved
2	Improved robot availability, ergonomics and worker acceptance.	Achieved
3	Dynamic safety zones offering a maximum of free space around the robot (maximal workspace size for human).	Achieved
4	Increased process integrity	Achieved
5	New application areas in non-typically automated industries	Achieved
6	New technology enables safe HRC in new applications. As a certified sensor system the SAPARO technology allows to optimize the safety requirements "Minimum (safety) distances" and "separation monitoring" from ISO 10218 on a new manner.	Achieved
7	Currently it is planned by Pilz to commercialize the SAPARO technology as a Pilz product. In case of patent Fraunhofer IFF (perhaps together with Pilz) will license the technology. Moreover Fraunhofer IFF will apply the knowledge from SAPARO project for future projects concerning HRC.	Achieved

Section 1.5: Dissemination KPIs

#	Description	status
1	Website	Achieved
2	IFF Wissenschaftstage 2015	Achieved
3	IFF Wissenschaftstage 2017	Upcoming
4	YouTube Video 1	Achieved
5	YouTube Video 2	Achieved
6	YouTube Video 3	Upcoming
7	ICRA 2016	Not Achieved
8	IROS 2016	Not Achieved
9	Maschinen Markt, Computer & Automation, Industrieanzeiger	Deviated
10	Hannover Messe 2016	Not Achieved
12	Automatica 2016	Timely achieved
13	Industrial Robot Journal	Upcoming

A complete list of dissemination activities and achievements is given in section 2.4.

Section 2: Detailed description

Section 2.1: Scientific and technological progress

Task 1: Technical specification

Task 1 started with the technical specification of the sensor system that comprises the technical requirements on the tactile floor as well as the projection system. Firstly, the size of the shared human-robot workplace was specified to an area of 4.0 by 6.0 meters that is sufficient to demonstrate the dynamics of the safety zones as well as to estimate the human's behavior. On basis of this we defined 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 that is well-suited to robustly detect the footprints of humans.

For illuminating the entire shared workspace of 4.0 by 6.0 meters a minimum of 4 projectors are necessary that were mounted on a system carrier in a height of about 4 meters. The projectors feature a resolution of 1280 by 800 pixels and have a luminous flux of 4000 lm that is sufficient to project images with high resolution and that is further bright enough to see them despite additional external illumination.

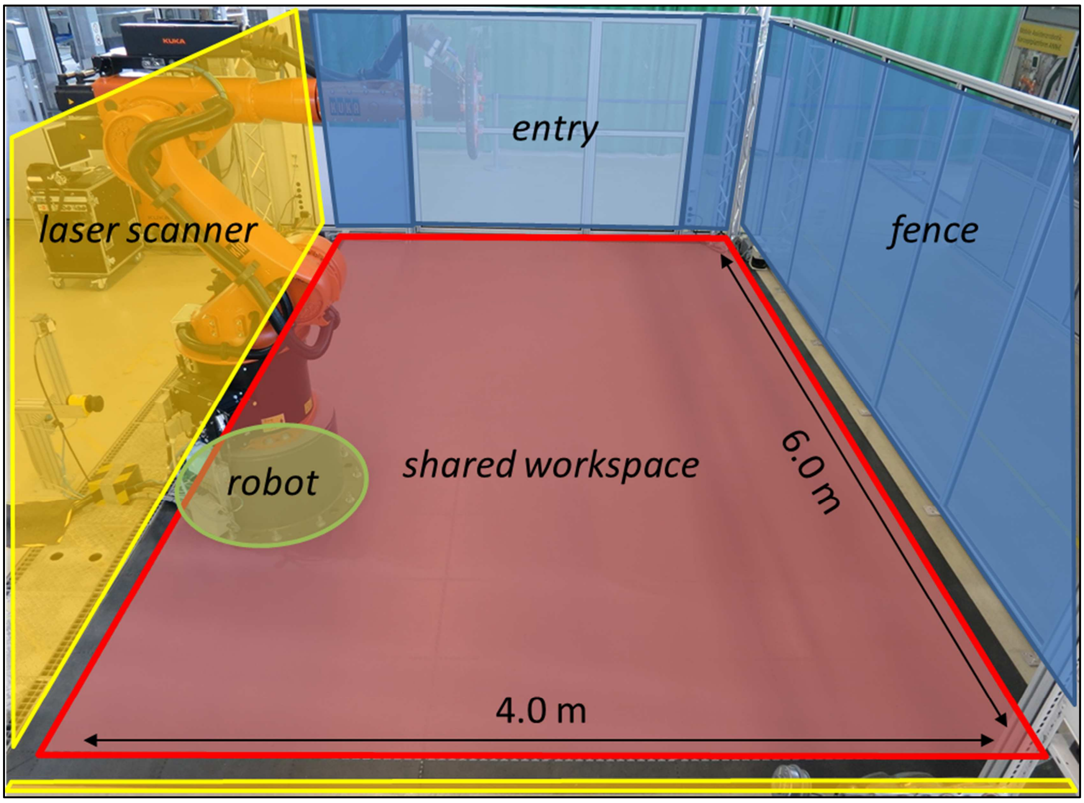

Figure 1: Human-robot shared workplace with a KUKA KR60 and a dimension of 4.0 by 6.0 meters.

As the proposed safety concept is not certified yet we needed additional safety equipment for safeguarding the shared workplace. 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 are safeguarded by safety laser.

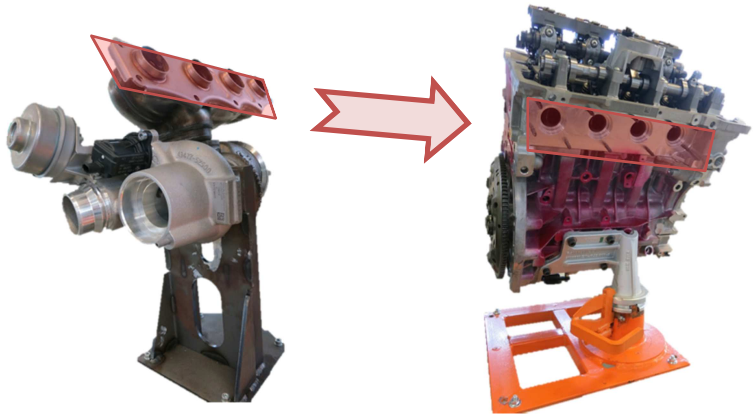

Figure 2: The scenario comprises the assembly of a turbocharger (left) and a motor block (right).

Furthermore, we defined the human-robot cooperation scenario and specified the use-case. The scenario comprises the handling of a turbocharger (see figure 2, left) that has to be equipped on a motor block (see figure 2, right). The robot (KUKA KR60 L45) will grasp the turbocharger and moves it autonomously to the motor block while the movement is monitored by the dynamic established safety spaces of the tactile floor. The projection system is visualizing the current active safety spaces and depicts additional process and robot related information. The turbocharger is mounted manually by the human to the motor block.

We further defined the interconnection of the hardware components and data transfer that is depicted in the following scheme (figure 3).

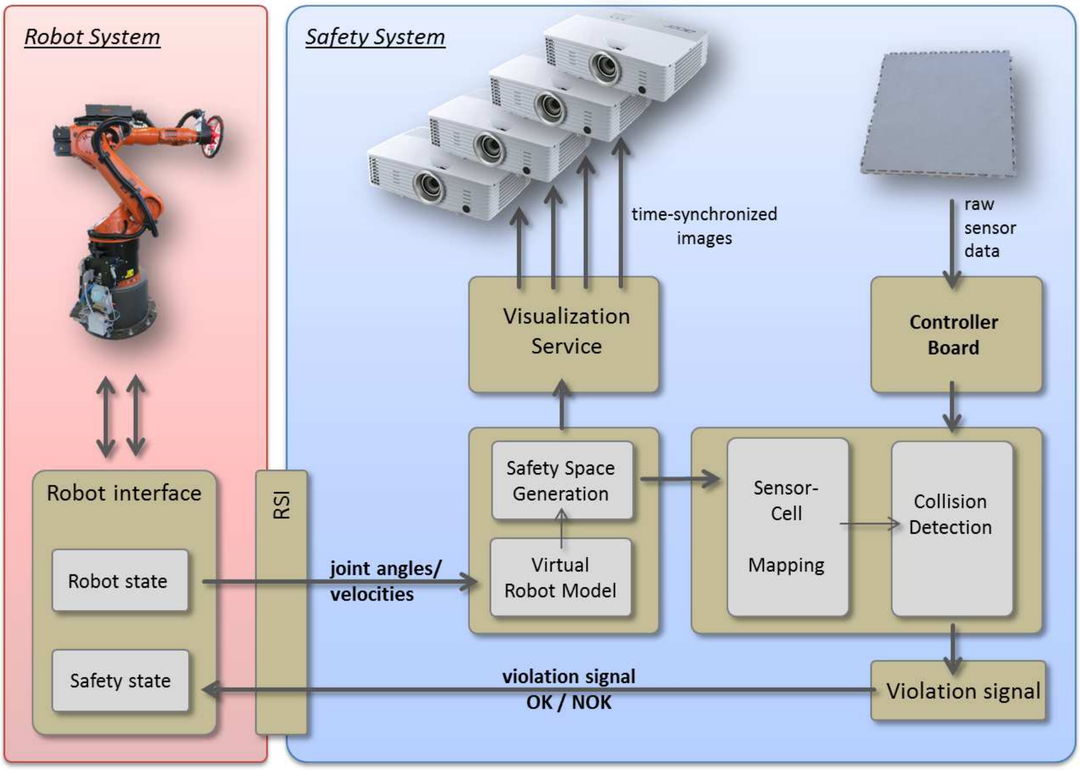

Figure 3: Overall scheme of the safety system representing the main parts of software and hardware components.

Task 2: Tactile floor development and adaption

The objective of this task was the design and setup of the tactile floor that is responsible for the hard safety aspect of the human-robot collaboration workplace. Moreover, this sensor system has to meet the requirements for robust detection and localization of humans. The developed floor covers an area of 4.0 by 6.0 meters and consists of 96 sensor tiles whereas a single tile has a size of 0.50 by 0.50 meters and includes 4 by 4 sensor cells. The tiles can be easily interconnected by conductor band and allow a fast buildup of the entire floor that can be seen in figure 4.

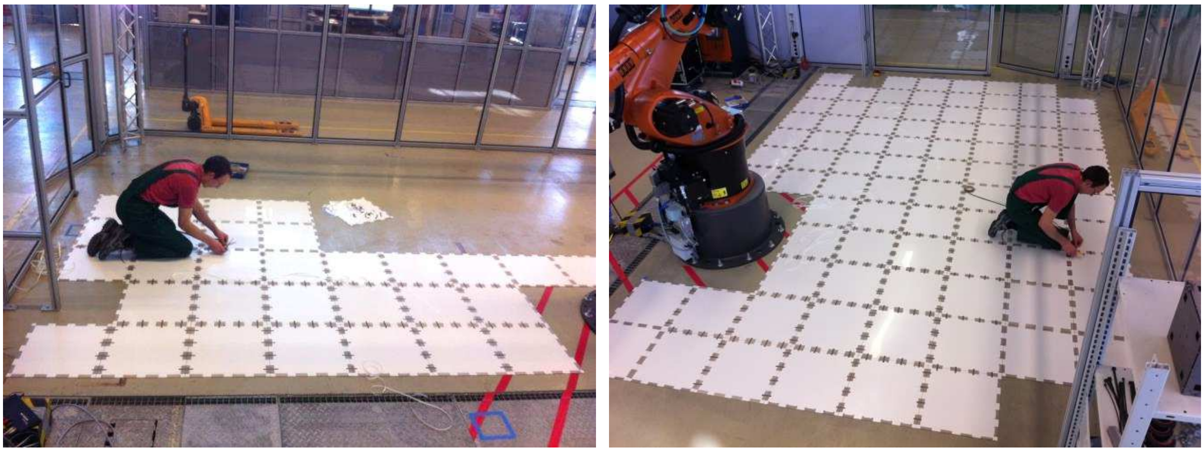

Figure 4: Buildup of the tactile floor that consists of single sensor tiles.

Finally, the sensor tiles are covered by industrial mats as seen in figure 5, left. The entire workspace with the complete tactile floor is depicted in figure 5, right.

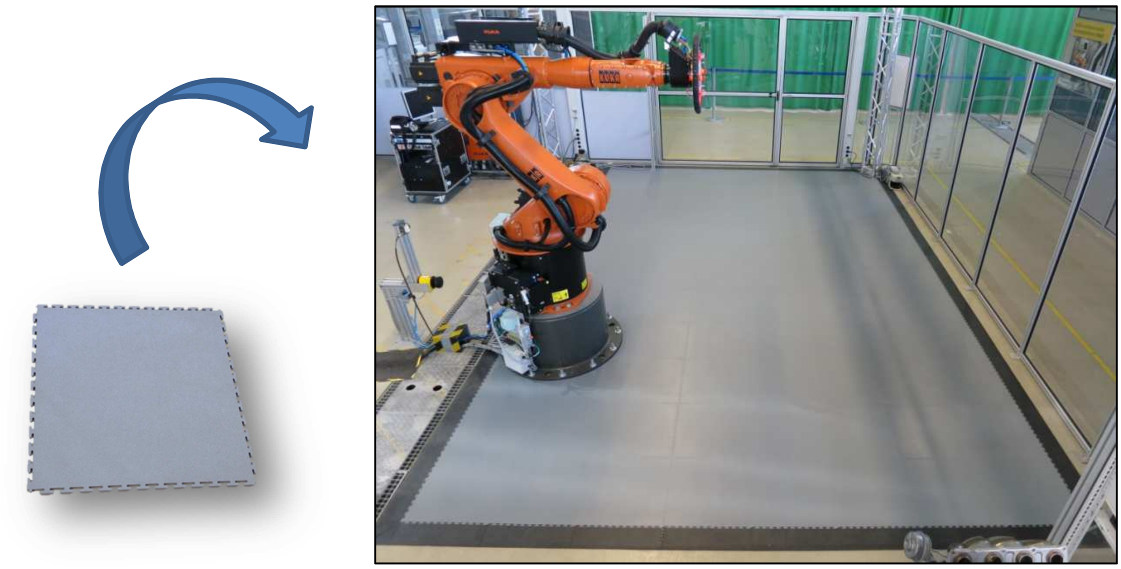

Figure 5: Finished tactile floor: Industrial mats (left) cover the underlying sensor tiles.

Besides the physical setup we developed and implemented a controller board (see figure 6) 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 some sensor specific adjustments like the thresholding of the trigger signal of a sensor cell at detected contact. The entire tactile floor comprising the hardware (sensor and industrial flooring), electronics/ controller and the communication to the PC were brought into service.

Figure 6: Developed controller board to measure sensor data and to communicate with PC.

Task 3: Projection system development and adaption

Task 3 concerns the development and adaption of the projection system for that we build up a system carrier to mount the 4 projectors in about 4 meters height, thus the entire tactile floor (i.e. human-robot shared workspace) can be illuminated (see Figure 7). The projectors have a resolution of 1280 by 800 pixels and an illumination intensity of 4000 lumen. They were connected by HDMI cables to a NVIDIA NVS 510 graphics card that allow a time synchronized image projection.

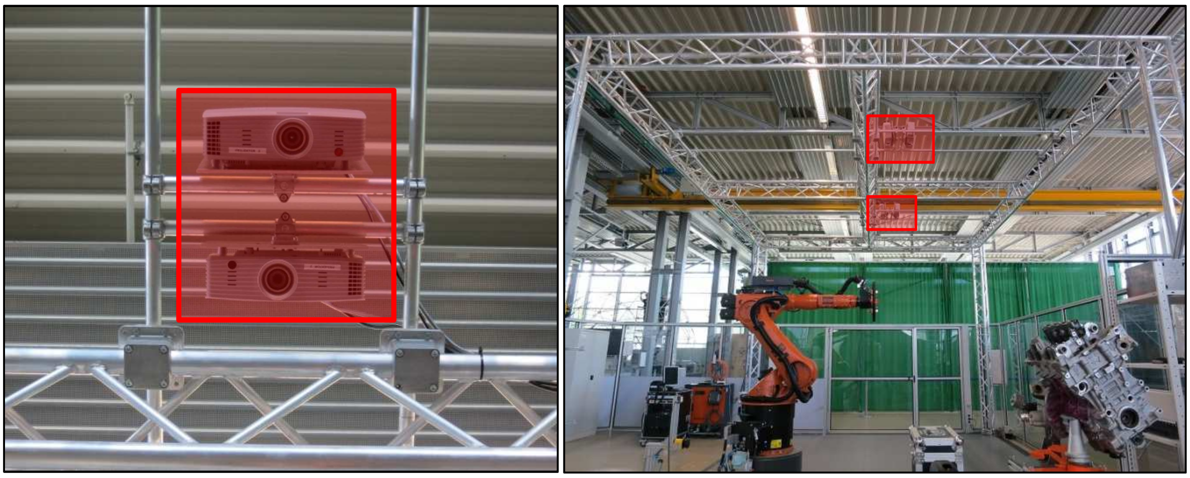

Figure 7: System carrier and mounted projectors in about 4 meters height.

The main challenge in this task concerns the intrinsic calibration of the four projectors. For that we developed and implemented a particular robot process to support the entire calibration process (see figure 8).

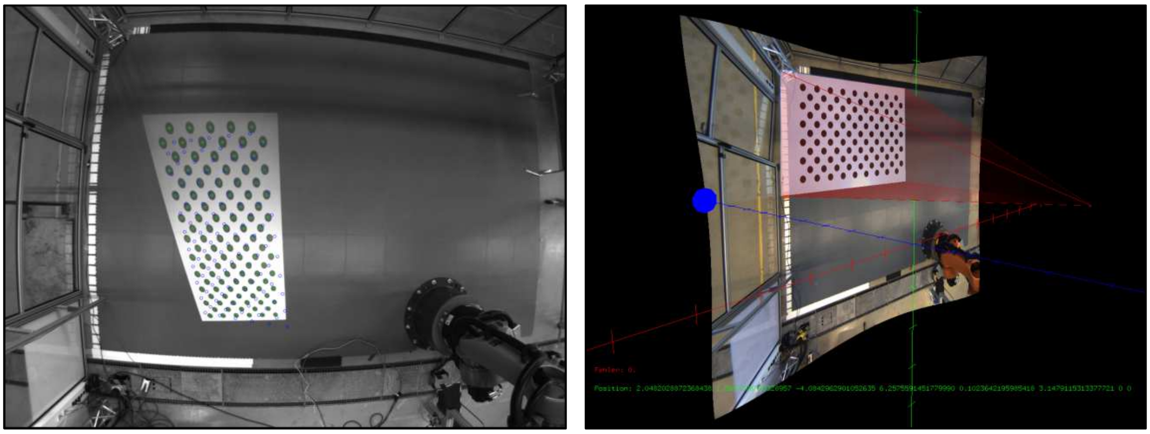

Figure 8: Robot supports the process of projector's intrinsic calibration (left) and extrinisic calibration (right).

Further on, we implemented software to generate time-synchronized images that will be warped and composed to an entire seamless image visualized at the surface of the tactile floor. The projection system was brought into service and can be used to visualize any safety-specific, process-specific or robot-specific information.

Task 4: System integration

This task aimed on integrating all hardware and software components to an entire working system. Main steps included the calibration to a common coordinate system of all hardware components that comprises the tactile floor, robot, and projectors. Furthermore, 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.

In the second part of Task 4 we implemented the industry-oriented human-robot cooperation scenario that aims on supporting the human while assembling a turbocharger and motor block. Here, 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 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 9 depicts the single steps of the scenario:

1. Autonomous movement of the robot to grasp position
2. Hand-guiding the robot and grasping the turbo-charger
3. Autonomous movement of the robot to motor block

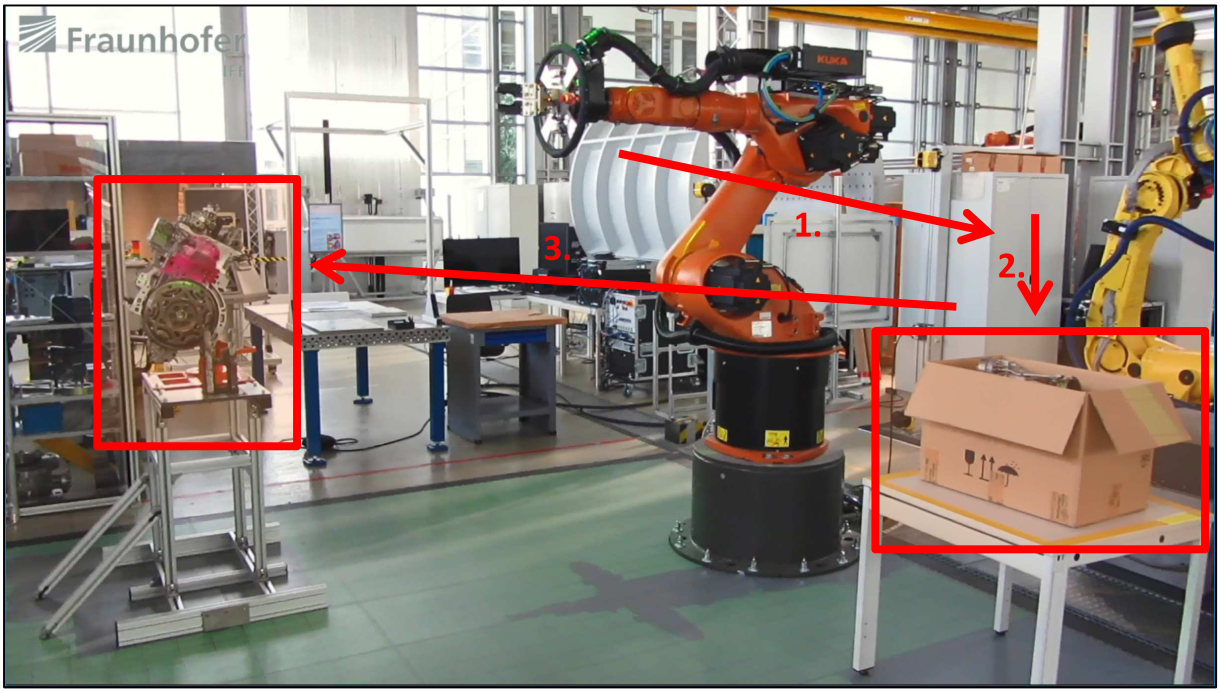

Figure 9: Single steps of the assembly process: Mounting a turbo-charger to motor-block.

Task 5: Implementation of safety space generation algorithms – tactile floor

The development and implementation of the individual safety space generation approaches are performed in this task. 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 to visualize and evaluate the results (see figure 10).

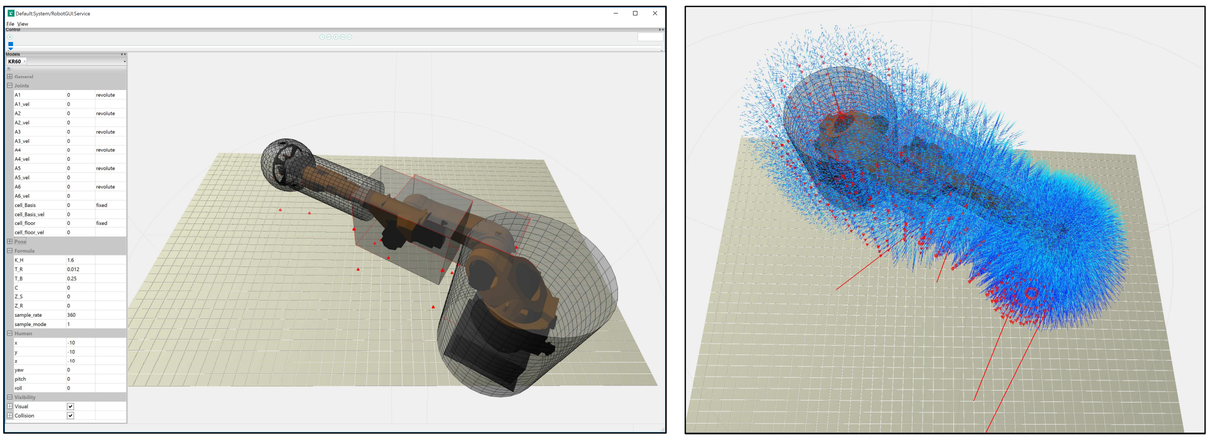

Figure 10: Simulation environment used to develop and implement the single safety approaches that are based on the distance formula described in ISO TS 15066. Right: Resulting safety distances (blue) at robot movement by a joint (A1) velocity of 0.8 rad/s.

This tool allows defining angles and velocities of every robot's joint and visualizes the robot's geometry accordingly. Further on, the user can define the parameters of the distance formula like brake distance, reaction time, human's speed and constants. It is also possible to define a human's position, movement direction and speed. The robot as well as the human is approximated by particular collision primitives to reduce the overall computing complexity. As the processing of the entire set of 3-dimensional distance vectors was 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 generated safety space is further used to 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.

Another point in Task 5 concerns the development of algorithms for estimating the human's behavior while moving on the tactile floor. It is based on detection and localization of "blobs" that consist of a set of single triggered sensor cells activated by the human's foots. These blobs are further correlated over time and form the basis for estimating human's steps that is used to approximate the human's movement direction and speed.

Task 6: Implementation of visualization approaches – projection system

The projection system implements the soft-safety aspect of the safety concept. The visualization of safety-, robot- and process-specific information will lead to improved ergonomics, user acceptance and robot availability. Further on, the projection system can act as worker assistance system supporting the user at work. First of all, we used it to visualize the area of the dynamic generated safety zone to the user. Here, it visualizes the sensor cell grid of the tactile floor and depicts the different safety zones by particular colors (green, yellow, red) while sensor cells that measured a contact are colored white (see figure 11).

As individual sensor cells are used to interact with the system at a triggered contact, these sensor cells are marked by a particular symbol (see figure 12, left). These interactive buttons can be used to control the robot (start/ stop robot's movements), activate a certain task or stop the process. We further visualize intended movements and destination positions of the robot. So, the user is always aware of the next robot's movements. In general, we can visualize any graphical representation, textual descriptions or schemes at certain positions in the workspace.

We further visualize the human's behaviour by a white circle representing the estimated position and a red line that points in movement direction. The length of the line demonstrates the speed of the movement (see figure 12, right).

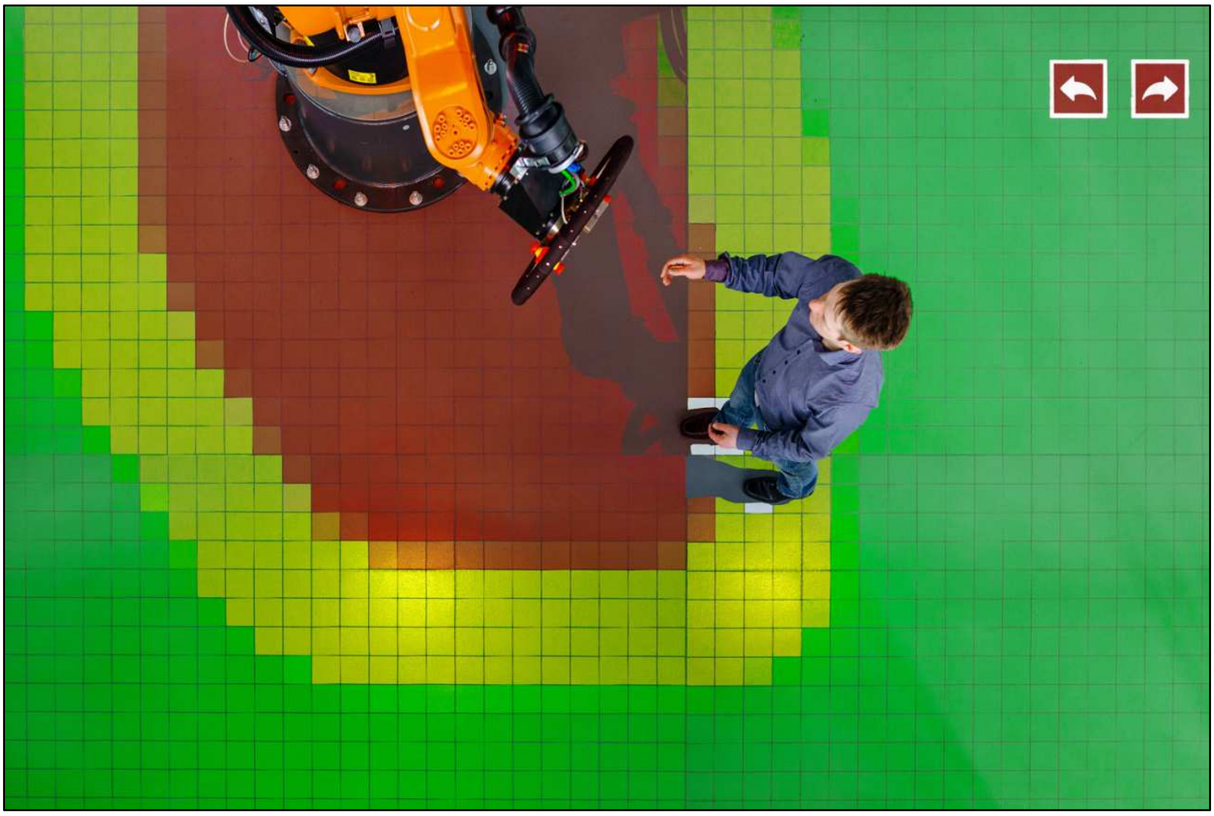

Figure 11: Dynamic generated safety zones that consist of a critical zone (red area), warn zone (yellow area) and free zone (green area).

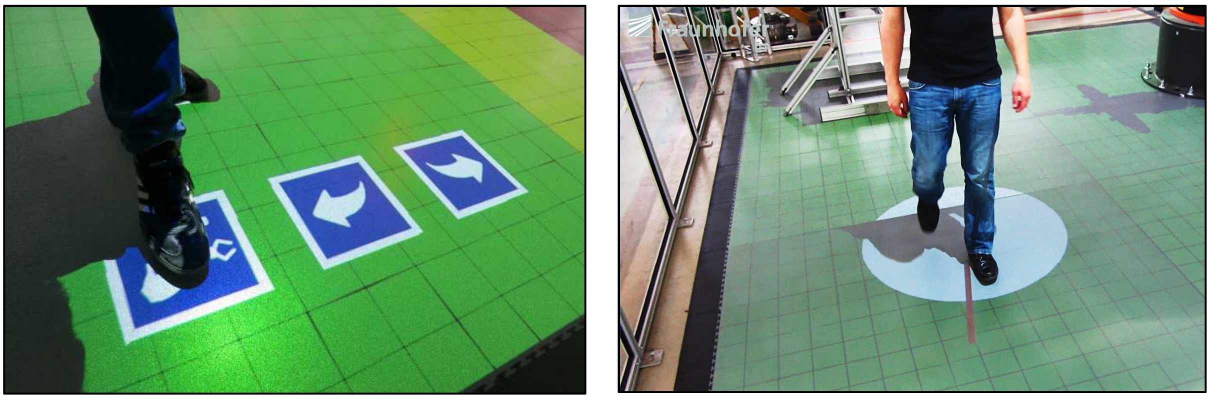

Figure 12: Left: Visualization of interactive buttons used to control the robot and system. Right: Visualization of approximated movement direction and speed of the human.

Task 7: Execution of experiments

In Task 7 we evaluated the estimation of the human's behavior that is based on the sensor data of the tactile floor. The latency times, jitter and noise of the sensor data entail a further optimization of the algorithms to improve the estimated movement direction and speed. Actually, the algorithms can handle one person robustly.

Secondly, we compared the individual safety approaches with each other. The safety approaches are:

1. Fence guard and safety laser scanner
2. Tactile floor: Semi-Static on basis of planned trajectory
3. Tactile floor: Dynamic on basis of current robot state
4. Tactile floor: Dynamic on basis of current robot state and human behavior

As foreseen, the traditional safety approach #1 is not suitable for human-robot cooperation scenarios. Safety approach #2 allows a safe cooperation of human and robot in a shared workspace. The resulting size of the semi-static safety zone depends on the length of the planned trajectory. Thus, the difference between safety approach #2 and safety approach #3 is significant for robot trajectories that comprise extensive movements of the robot. The size of the safety zone concerning safety approach #3 depends on the current robot's joint angles and velocities. As the human's behavior is not considered the size of the safety zone is nearly maximal as the human may approach the robot from any position with maximal speed. This safety approach is depicted in figure 13. In safety approach #4 the human's behavior is also incorporated to determine the size of the safety zone. As depicted in figure 14, the safety zone is minimal but always extended in direction of the human's position. The width of the extension depends on the human's movement direction and speed. If the human moves straight to the robot this extension is maximal.

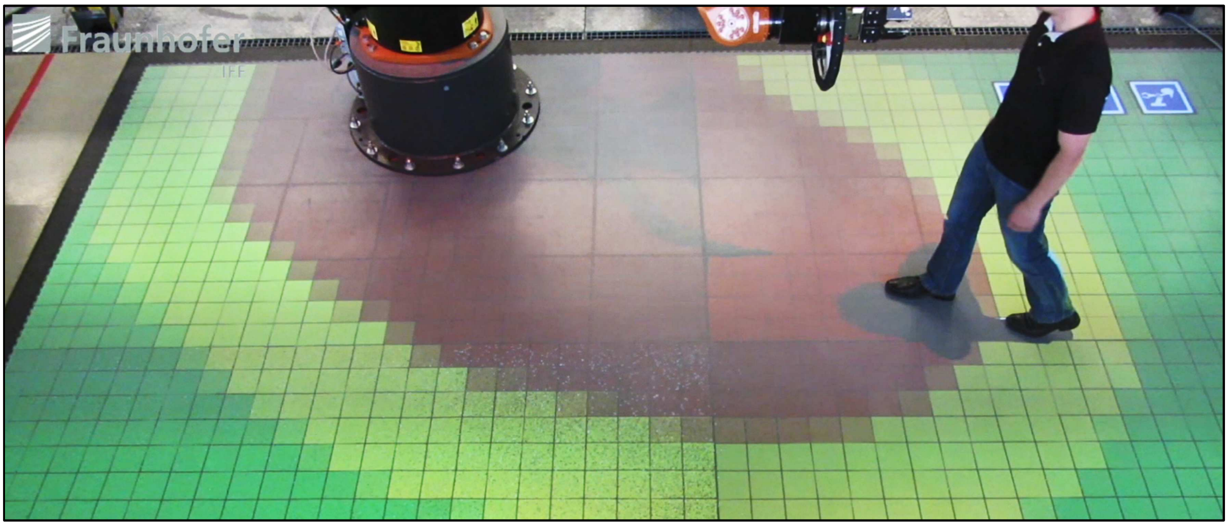

Figure 13: Safety approach #3: Size of the safety zone depends on current robot's joint angles and velocities.

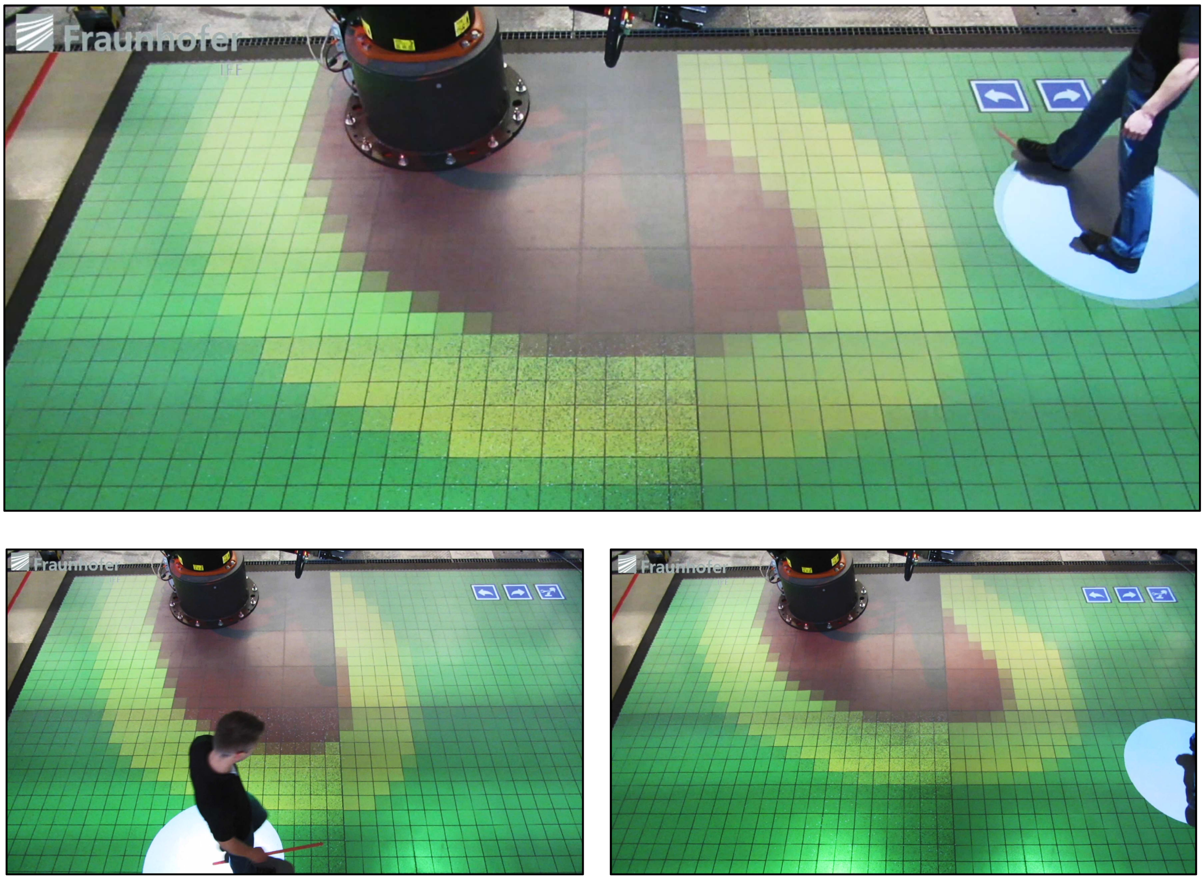

Figure 14: Safety approach #4: Size of the safety zone depends on both robot's behavior and human's behavior.

Section 2.2: Scientific and technological achievements

- <u>People reliable detection</u>: In contrast to other monitoring systems that are mainly based on visual operating principles, the tactile floor is very robust concerning environmental conditions. Changes in lighting conditions do not affect the sensor measurements. Objects and humans with a minimal weight of 10 kilograms (can be adjusted) are robustly detected. The resolution of 0.125 by 0.125 meters (can be adjusted) of an individual sensor cell is sufficient to detect the footprints of humans.
- <u>Efficient estimation of direction and speed of movement</u>: Besides robustly measuring the distance between human and robot for safeguarding the human, the sensor measurements of the tactile floor can be also used to approximate the human's movement direction and speed. The approach formula described in ISO TS 15066 incorporates the human's behavior to determine the safety distance between human and robot. So, the tactile floor implements the cooperation strategy of a "speed and separation monitoring" system. Actually, with current implementation the behavior of one person is reliably estimated.
- <u>Gains in process integrity due to soft-safety components:</u> The projection system allows the visualization of safety-, robot- and process-specific information directly into the human's workspace. As the visualization of process-specific information supports the user at work (worker-assistance) or helps to manage the system (error handling), the robot-specific

information may be used to depict robot errors as well as intended movements and destination positions of the robot. This in combination with the visualization of safety-specific information like the boundaries of the safety zones will lead to increased robot availability because of the human's awareness concerning the robot's behavior and safety zone's dimension. The human can actively avoid harmful situations that leads to less safety violations (robot stops) and results in increased process integrity.

- Ease-of-use of the tactile floor mat: Ease-of-use was demonstrated by build-up of the tactile floor within half-day work by two persons. The design of the tactile floor is user-friendly as it consists of single sensor tiles that are simply interconnected by conductor band. After connecting all sensor tiles the tactile floor is finished by an industrial covering that is robust concerning heavy weights and protects the underlying sensors from damage.
- System efficacy: The overall system efficacy represents the impact of the developed safety concept to human-robot enabled workplaces. This safety system allows a robust detection of objects and humans in the shared workspace of both human and robot while it visualizes useful information to the user. It was shown that the combination of tactile floor and projection system is well suited for such applications. In general, this safety concept implements for the first time the human-robot cooperation mode "speed and separation monitoring" as the safety zones are generated by using the current robot's state and current human's behavior. These dynamic generated safety zones are based on the approach formula described in ISO/TS 15066.

Section 2.3: Socio-economic achievements

- Providing a novel solution (safety concept) for safe human-robot collaboration: A novel safety concept consisting of a tactile floor and projection system was developed. Concerning the current state of the art of safety techniques the SAPARO safety concept is a step-change for future human-robot cooperative workplaces with high payload robots. The combination of tactile floor and projection system is well-suited to safeguard and support the human in flexible manufacturing processes with shared human-robot workplaces with high-payload robots.
- Improved robot availability, ergonomics, worker acceptance: In contrast to other safety systems that doesn't provide any information to the user the SAPARO system visualizes safety-specific, robot-specific and process-specific information that supports the user at work. As the user is aware of intended movements of the robot as well as current safety zone borders, violations of the safety zones can be actively avoided and leads to an improved robot and process availability. Moreover, the visualization of robot's state leads to an understanding of the robot's behavior and results in improved acceptance. Using process-specific information the system may also support the human's work by visualizing helpful information like textual description, schemes or images (worker assistance).
- Dynamic safety zones offering a maximum of free space around the robot: The implementation of the approach formula described in ISO/TS 15066 leads to dynamic safety zones that are generated by using both the current joint angles and velocities of the robot as well as by using the current human behavior. Actually, the usage of the human's movement direction and speed for determining the safety zone's dimensions allows an adaption of the robot's movement

velocity that is optimal (maximal) in all situations. In general, the approach formula will offer a maximum of free space to the user.

- Increased process integrity: The improved robot availability because of the user-centered visualization of information by the projection system directly results in increased process integrity.
- New application areas in non-typically automated industries: The SAPARO system may be also very beneficial in application areas like aircraft industry. As this industrial area focusses on new automation technologies like mobile manipulators, the application of novel safety concepts is necessary. Further on, the SAPARO concept may be helpful in security applications for protecting objects (in museums) or for interaction purposes in games.
- New technology enables safe HRC in new applications: As a certified sensor system the SAPARO technology allows to optimize the safety requirements “Minimum (safety) distances” and “separation monitoring” from ISO 10218 on a new manner, because of the implementation of the approach formula in ISO TS 15066 that leads to minimal safety zones or rather maximal robot speed at any time.
- Safety-certification of the SAPARO safety concept: Currently, Pilz is developing a commercial safety-certified version of the tactile floor used in the SAPARO experiment. As this is based on the Fraunhofer IFF’s patent, IFF will license this technology. Additionally, the IFF filed a patent that comprises also the soft-safety aspect which handles the visualization of safety-specific and robot-specific information like current safety zones as well as intended robot movements. Pilz is very interested in the SAPARO safety concept and it is a main aspect of future cooperation between IFF and Pilz.

Section 2.4: Dissemination activities

#	Type of publication/ event	Title of the article/ presentation/ demonstrator	Title of the periodical/ series/ conference/ book/ event	Place	Date	Comments, especially references, links, …
1	*Website*	*SAPARO*	*Homepage of Fraunhofer IFF, Robotic Systems Business Unit*		*continuous*	*http://www.iff.fraunhofer.de/en/business-units /robotic-systems/saparo.html*
2	*youTube Video*	*SAPARO*	*Fraunhofer IFF youTube channel: fraunhoferiff*		*continuous*	https://youtu.be/kXKwb7PEALk https://youtu.be/sykfaMuuVEI
3	*Television report*	*Am Roboter geht kein Weg vorbei*	*N24*		*04.06.2015 - continuous*	*http://www.n24.de/n24/Mediathek/videos/ d/6754606/am-roboter-geht-kein-weg-vorbei.html*
4	*Exhibition*	*SAPARO – Safe Human-Robot Cooperation with high payload robots in industrial applications*	*Lange Nacht der Wissenschaft 2015*	*Fraunhofer IFF, Magdeburg, Germany*	*30.05.2015*	*Presented the experiment and demonstrated the current prototype to the public from 06:00 p.m. until midnight.*
5	*Exhibition*	*SAPARO – Safe Human-Robot Cooperation with high payload robots in industrial applications*	*IFF Wissenschaftstage 2015*	*Fraunhofer IFF, Magdeburg, Germany*	*24.06. – 25.06.2015*	*Presented the experiment and demonstrated the current prototype to the public from industry and academia. Total of 160 specialists visited the symposium and exhibition.*

6	*Video presentation*	*SAPARO*	*2015 IEEE/RSJ International Conference on Intelligent Robots and Systems*	*Hamburg Germany*	*28.09. – 02.10.2015*	*Video presentation of the SAPARO experiment at the ECHORD++ booth at IROS 2015.*
7	*Television report*	*This German Machine is Hitting People to Make Tomorrow's Robots Safer*	*Bloomberg Technology* *Bloomberg Business*		*11.11.2015 - continuous*	*http://www.bloomberg.com/news/articles/2015-11-11/robots-now-punch-people-to-make-tomorrow-s-machines-safer*
8	*Poster presentation*	*Safe Human-Robot Cooperation with high payload robots in industrial applications*	*11th International Conference on Human-Robot Interaction (HRI)*	*Christchurch, New Zealand*	*07.03. – 10.03.2016*	*Accepted paper and poster presentation at HRI 2016.*
9	*Video presentation* *&* *Exhibition*	*SAPARO*	*7th International Trade Fair for Automation and Mechatronics*	*Munich, Germany*	*21.06. – 24.06.2016*	*Presentation of the SAPARO experiment by video at the "Fraunhofer IFF" in hall A4, at booth 129 as well as on the exhibition area "ECHORD++" in hall B4, booth 317.* *We also presented the tactile floor by a live demonstrator to the public.*
10	*Magazine*	*Grundlagenforschung und innovative Entwicklungen für eine sichere Mensch-Roboter-Kollaboration*	*Betriebliche Prävention*		*Volume 10, 2016*	*Besides other technologies description and explanation of SAPARO experiment. Pages 374 – 377.* *http://www.beprdigital.de/*
11	*Magazine*	*So schützen Sie Ihre Mitarbeiter vor Robotern:* *Die 9 sichersten Methoden*	*Produktion*		*Volume 12, 2016*	*Presentation of the SAPARO safety concept as one of nine safety technologies. Pages 8 – 10.* *https://www.produktion.de/*
12	*Magazine*	*Assistenzrobotik und sichere Mensch-Roboter-Kollaboration im industriellen Umfeld*	*Unternehmermagazin*		*[Tbd]* *2016*	*http://www.unternehmermagazin.de/*
13	*Permanent presentation & Stand-up display*	*SAPARO*		*Fraunhofer IFF, technical center*	*continuous*	*The demonstrator is permanently presented and demonstrated to guests in our technical center. The experiment is additionally described by a stand-up display.*

Section 3: Resource usage summary

Matter of expense	Costs in EURO
Personal costs	**337.939**
Material/ Travel etc. costs	**16.439**
Technical equipment	**0**
Overall costs	**354.378**

Section 4: Deviations and mitigation

- *Explain deviations reported in the previous sections and steps taken to mitigate them. Max 10 sentences per item. Feel free to put pics/video links.*

Section 5: Future work

- The algorithms for estimating the human's behavior can be further improved. Here, it may be very interesting to develop algorithms for estimating the behavior of more than one person.
- There is also some potential for enhancements regarding the interaction by the virtual buttons. The position and functionality may change with respect to the current process/task and position of the human.
- The algorithms for generating the dynamic safety spaces can be further improved regarding real-time capabilities.
- Intensify cooperation with Pilz to commercialize the SAPARO developments.
- Providing the tactile floor to universities as research platform (just in preparation - TUM)
- Publish a research paper presenting the insights of the SAPARO experiment.