Portable Safety System using Radar for Flexible Human-Robot-Collaboration in a Real Semi-automated Production Line

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Abstract: The implementation of a reliable vision system for a human-robot environment is a key issue for the collaborative production industry. The core challenge of human-robot collaboration is to ensure safety. Furthermore, a flexible safety system is required for frequently changing applications and work areas. This paper focuses on the development and application of a workspace monitoring system for safeguarding using radar sensors. The human-robot collaboration cell is designed to enable a flexible integration regardless of the work location. This results in higher productivity. Since no separating protective devices are provided for the cell, safety-oriented monitoring and control by suitable safety sensors is required. The methods to minimize the size of the necessary safety distance will be presented. The experimental validation shows that this safety system with radar sensors performs a reliable workspace monitoring system. The high robustness, reactivity and flexibility of the safety concept makes this system usable for collaborative tasks in a real industrial environment.

1 INTRODUCTION

The assembly and installation of mechatronic products in small and midsize companies is mostly indicated with a high number of variants, which leads to a low number of order quantities. Consequently, there are high requirements on the flexibility in a production line and the assembly, which presupposes a high number of employees. In contrast, the automation level in the final assembly of the products is relatively low. Because of the continuously increasing shortage of skilled labor, the degree of automation needs to be increased. The use of collaborative robot systems that can be flexibly integrated into an existing production line has the potential to solve this problem. Most of the work steps combine filigree work that can be done by the human and monotonous work that can be done by the robot. This requires a collaboration, which leads to an overlapping work area of both parties. Therefore, a flexible safety system for human-robot collaboration is indispensable that can be integrated to different workplaces without individual safety considerations. In our research, we present a safety system that is completely mounted on a mobile robotic cell so that no modifications of workplaces is necessary. In addition, the configuration of the safety system, when it is moved to a different workplace, is done automatically. Above all, the system conforms to all the current international safety standards. In this paper, the transfer from scientific findings into a real industrial environment will be outlined.

2 RELATED WORK

With the introduction of collaborative robots in industry, the field of robot safety has been redefined. Certain conditions are required for the collaborative approach. Thus, safety standards such as *DIN EN ISO 10218* part one (DIN Deutsches Institut für Normung, 2011) and two (DIN Deutsches Institut für Normung, 2011) have been introduced, which identify specific applications and criteria. The safety

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requirements for collaborative robot systems and the working environment have been extended by the technical specification *ISO/TS 15066* (DIN Deutsches Institut für Normung, 2016). This complements the requirements and guidelines for collaborative robot applications. It is possible for the robot to move even if the human is working in the same workspace. For this collaboration, the safety system is the predominant aspect for the successful implementation in a real industrial environment. The state of the art presents many possible solutions.

2.1 Safety Concepts for Human-Robot-Collaboration

Lasota et al., define four main methods to provide safety for a human-robot system: motion planning, prediction, control and consideration. According to motion planning, the safety system can be subdivided into collision avoidance and collision recognition (Lasota, Fong, & Shah, 2020).

The first one is presented by *Vogel et al.* in their research to implement a projection- and camera-based safety system. Depending on the position and the velocity of the robot, a well-shaped and dynamically adapted safety space is projected on the table. If an object disrupts the emitted light rays of the projector, the robot stops its movement to avoid any collision with the human (Vogel, Walter, & Elkmann, 2013; Vogel, Walter, & Elkmann, 2017).

On the contrary, *Kulic and Croft* present a safety system that is dodging obstacles instead of inducing an emergency stop. The distance is determined by a stereo-camera at the bottom of the robot to catch the human and the trajectory of the robot. Thus, the system can predict a potential collision and avoid it (Kulic & Croft, 2005).

In their research *Berg et al.* present an approach to integrate safety elements into a task-oriented programming system to increase the flexibility for human-robot collaboration. Safety aspects are considered by a planning, programming and operation module as well as a safety-check before operation (Berg, Richter, & Reinhart, 2018).

Antonelli et al., introduce a safety system for a flexible and safe interactive human-robot environment in small batch production. The idea is to integrate a so-called *Superior Hierarchical Controller* that is used as interface between the human and the robot. The controller gathers information from safety sensors, e.g. laser scanner at the bottom, as well as from smart cameras that are located over the working area of the robot (Antonelli, Astanin, Caporaletti, & Donati, 2014).

A radar-based safety system for estimation of the distance between the robot and human is presented by *Zlatanski et al*. The researchers compared static and dynamic characteristics of the radar sensor with a state-of-the-art laser scanner. The experimental set-ups show that both sensor types are performing comparable to each other in respect of the field of view, resolution and reaction time (Zlatanski, Sommer, Zurfluh, & Madonna, 2018).

Amin et al. are presenting a mixed-perception approach for safe HRC in industrial automation using deep learning networks and AI for action recognition and contact detection. The action is monitored using a skeleton model of the human inside the workspace. The physical contact is distinguished between intentional and accidental interaction. The results show a high potential for AI-driven solutions for the safety in HRC (Amin, Rezayati, Venn, & Karimpour, 2020).

A new collaborative robot skin (CoboSkin) for HRC is presented and investigated by *Pang et al*. The skin consists of inflatable and sensing units. The latter ones are able to measure the force in real-time. By adjusting the internal air pressure, the stiffness of the skin can be varied. The results show that the impact force during a collision of human and robot can be reduced by adapting the air pressure (Pang et al., 2021).

Other related safety concepts in the field of HRC are investigated in(Salmi et al., 2013; Dohi et al., 2018; Halme et al., 2018; Hoskins, Padayachee, & Bright, 2019; Matthias et al., 2011).

2.2 Sensor Systems for Human-Robot-Collaboration in Real Industrial Environments

In most of the real industrial applications, the safety system for human-robot-collaboration is realized by the reduction of speed and force in order to fulfill the requirements given by the ISO/TS 15066. (KUKA Systems GmbH, 2018) (Glastechnik Hofmann GmbH, 2017)

Furthermore, *Rexroth* developed the so-called APAS assistant mobile (Rexroth, 2014), which is a mobile collaborative robotic system that can be flexibly used at different workplaces. The safety system consists of a capacitive sensor skin that detects the presence of a human before a collision occurs. In this case, the robot is switched to a safety stop. When no worker is nearby the robot, it is moving with a reduced speed.

The *SafetyEYE* is one of the first safe camera systems for 3D room monitoring (PILZ, 2014). It offers new possibilities for monitoring and safeguarding danger zones. The sensor system detects and reports the intrusion of objects into warning and detection zones, which can be freely defined. For the flexible installation, at least four markers have to be placed on the floor of the supervised area.

The current state of the art presents many possible solutions that are listed and compared to the proposed safety system in this paper. Table 1 shows the result:

Table 1: Comparing the proposed system with related systems.

	Safety Stop When Triggered	Modify Workplaces	Mobile System	Individual Configuration	Flexibility	Allows Maximum Robot Speed	CE Mark
Vogel et al.	*no*	*yes*	*no*	*no*	*low*	*yes*	*no*
Kulic & Croft	*no*	*yes*	*no*	*no*	*high*	*no*	*no*
Antonelli et al.	*no*	*yes*	*no*	*yes*	*low*	*yes*	*no*
Amin et al.	*no*	*no*	*no*	*yes*	*low*	*no*	*no*
KUKA Systems	*yes*	*yes*	*no*	*yes*	*very low*	*no*	*yes*
Glastechnik Hofmann	*yes*	*yes*	*no*	*yes*	*very low*	*yes*	*yes*
Rexroth	*yes*	*no*	*yes*	*no*	*high*	*no*	*yes*
PILZ	*yes*	*yes*	*no*	*yes*	*very low*	*yes*	*yes*
Portable Safety System	*no*	*no*	*yes*	*no*	*very high*	*yes*	*yes*

The comparison makes clear that there is currently no safety system available on the market that has a high flexibility according to different workplaces, allows maximum robot speed, has a CE-Mark, do not lead to a safety stop, when it is triggered, needs no individual configuration on new workplaces, is mobile and needs no modification of the existing workplaces. Only the portable safety system in this paper fulfills all those requirements that are indisputable for the use in a real industrial environment.

For the methods of (Vogel, Walter, & Elkmann, 2013; Kulic & Croft, 2005; Amin, Rezayati, Venn, & Karimpour, 2020) the robot cell has to be adapted in order to integrate their systems. The safety system of (Antonelli, Astanin, Caporaletti, & Donati, 2014) is limited to specific workplaces and can not be flexibly used. The approach of (Amin, Rezayati, Venn, & Karimpour, 2020) is not conforming to safety standards. Thus, it can not be integrated into a real production line. The sensor systems of (KUKA Systems GmbH, 2018; Glastechnik Hofmann GmbH, 2017; Rexroth, 2014) lead to high cycle times and low productivity, because the robot is continuously moving with reduced speed. The system in (PILZ, 2014) has the disadvantage that it has a huge supervised area. It also has to be configured at every different workplace. Therefore, more research needs to be done in order to close this gap.

3 MOBILE ROBOTIC CELL

During the project *AdhocMRK* we wanted to define and develop a safety system for human-robot-collaboration that can be flexibly moved and integrated into a real semi-automated production line. The main research question is, how a sensor system for a movable and portable robotic application that also confirms to the international safety standards could be designed.

To put this system into operation in a real industrial environment, there are many requirements that have to be fulfilled. The safety system must not transfer the robot to a safety stop, when the sensors are triggered to increase the productivity. The existing workplaces must not be modified or remodeled. The entire sensor technology has to be mounted on the mobile robotic cell. The safety system has to be maximum adaptable to new workplaces so that no individual reconfiguration of the sensors is necessary. Finally, no individual safety assessment is supposed to be performed on a new workplace.

Current safety concepts are not able to fulfill all the requirements that are provided to the robotic system. The main reasons for this is that the robotic cell has to be movable and deployable on different applications. The existing safety concepts are not portable and thus limited to an individual workplace.

To cope with these challenges, we defined a sensor system for a mobile robotic cell that supervises the space in front and to the both sides of the robotic application including the considered workplace. To the front a safe laser scanner is used that is configured for hand detection. To the both sides, safe radar scanner are detecting the presence of a human. These sensors are configured with person detection. The sensors do not supervise the access from behind the workplace. Thus, e.g. a safety fence has to prevent a human from entering the robotic system. This so-called external safety system is completely mounted on the mobile robotic cell and detects the presence of a human nearby the working area of the robot. We also defined an internal safety system that is supervising the movement of the robot by the usage of safety planes.

According to the safety system, the robot can run in normal or reduced mode. In normal mode, the robot can move with maximum speed and force. The reduced mode can be initiated either by the external or by the internal safety system. In this mode the robot´s velocity and force is strictly limited, but not stopped. This leads to a reduction of cycle time, because the robot is still moving. Only when the robot collides with the human, a protective stop is initialized and the movement stops.

For the realization of the safety concept, we constructed and built a robotic cell that consists of the following elements (Figure 1). First, the collaborative robot (UR5e) including the teach-panel and the robot controller, which are mounted on a mobile platform. This platform can be moved to different workplaces manually via guide rolls. Second, a framework was constructed, on which the external sensor system, a signal tower as well as some pushbuttons and switches are installed. Third, a control cabinet, which involves the safe programmable logic controller (PLC), safe digital I/O modules, the power-supply unit for 24 VDC and the controller of the radar sensors.

Figure 1: Flexible and mobile robotic cell.

For the communication between the robot cell and an industrial workplace in a real scenario, a specific and standardized plug system is used. This plug contains of the power supply, compressed-air supply as well as digital I/Os for the controlling of the motion sequence of the robot. A toggle fastener realizes the firm connection towards the workplace. The plug and the toggle fastener make the mobile robotic cell applicable to different workstations in a real industrial environment.

4 EXTERNAL SENSOR SYSTEM

The sensor system for the mobile robotic cell consists of one safe Lidar Laser scanner from SICK, the S3000 Standard and four safe radar scanner from Inxpect, the LBK system. A PLC is used to unite the sensor data. The entire sensor system and all the described components are configured with two channels to conform the international standards. For each of the sensors specific safety distances, which are defined as the distance from the beginning of the supervised area by the sensor to the working area of the robot, have to be calculated.

4.1 Safe Lidar Laser Scanner with Hand Detection

To supervise the access of a human to the front of the robotic cell, the safe laser scanner is used (Figure 2). The sensor is working with the method light detection and ranging (Lidar).

Figure 2: Laser scanner to the front.

By measuring the time between sending and receiving of laser impulses, the distance can be calculated or respectively the presence of a human. According to the international standard DIN ISO13855 (DIN Deutsches Institut für Normung, 2010) the minimum safety distance $S_{min,\ Laser}$ to the front side, can be calculated by (1). The sensor is configured for hand detection which means that the sensor detection level d = 40 mm. This value represents the distance between two laser beams that are emitted by the sensor. The stopping time T is composed of the stopping time of the PLC, the laser scanner and the UR5e Cobot. The approach speed K is a constant value and is set to 1.600 mm/s according to the standard, which results with (1) in a minimum safety distance of $S_{min,Laser}$ = 640 mm.

$$S_{min,Laser} = K \cdot T + 8 \cdot (d - 14) \qquad (1)$$

The supervised area by the laser scanner is configured rectangular. Figure 6 shows the supervised area (A).

4.2 Safe Radar Scanner with Person Detection

The safe radar scanner are used to detect the access of a human to both sides of the robotic system (Figure 3).

Figure 3: Radar sensor for the detection to the sides.

The LBK system is based on a 24 GHz radar algorithm that filters out disturbances, e.g. smoke, dust, splashes or machining waste. This leads to a reduction of false alarms and thus increases the productivity. The sensor transmits the radio waves and identifies motion information by analyzing the returned signals reflected from both static and moving objects in the operating area. The sensor only detects the movement of objects, not the presence of an object itself, which is the biggest unique feature compared to a laser scanner. It is also automatically reconfigured on a new workplace with different environment, which makes the entire external safety system portable. The portability is given, when the robotic cell is added to a new workplace, where the surrounding always changes. The supervised area of the radar sensor can be adjusted with two variants concerning the two axes horizontal and vertical:

- wide protective area: 110° horizontal, 30° vertical
- narrow protective area: 50° horizontal, 15° vertical

According to DIN 13855 (DIN Deutsches Institut für Normung, 2010) the minimum safety distance $S_{min, Radar}$ to both sides of the robotic cell can be calculated by (2):

$$S_{min,Radar} = K \cdot T + C \qquad (2)$$

These sensors are configured for person detection, which implies a sensor detection level d = 70 mm. The stopping time T is composed of the PLC, the radar scanner and the UR5e Cobot. With the equal approach speed K as for the laser scanner and equation (2) the minimum safety distance $S_{min, Radar}$ = 1.242 mm is determined. Figure 6 shows the supervised are by the radar scanner to both sides (B). For the automatic restart of the robot with maximum velocity in normal mode, two more radar sensors are used to supervise the area that is not covered by the laser scanner and the radar sensors to both sides. In case a human worker enters the working area of the robot the safety system is triggered and the robot is set to reduced mode. Two additional radar sensors make sure that no human is inside the robotic cell. After a timeout of 10 s, the robot is set back to normal mode. Figure 4 shows the supervised areas for the automatic restart. To conform the standards, the radar sensors for the automatic restart have to be mounted in a specific height over the ground. According to DIN 13855 (DIN Deutsches Institut für Normung, 2010) the minimum height of the safety field H_{min} can be calculated by (3):

$$H_{min} = 15 \cdot (d - 14) \qquad (3)$$

With a sensor detection level of d = 70 mm and (3), the minimum height H_{min} is calculated with 300 mm.

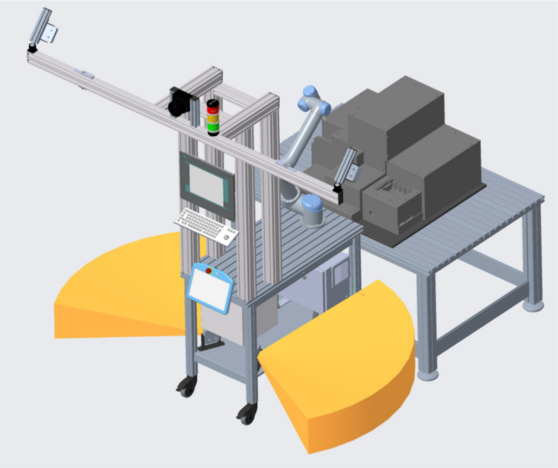

Figure 4: Supervised area for automatic restart.

4.3 Programmable Logic Control for Unification

The safe PLC is used for the communication between the robot controller and the external sensor system. Figure 5 shows the configuration of the PLC. If one of the two sensor types (radar or laser) are triggered, because a worker is entering the supervised area, the two-channeled digital outputs of the PLC to the robot controller are switched to FALSE. This transfers the robot into the *reduced mode.*

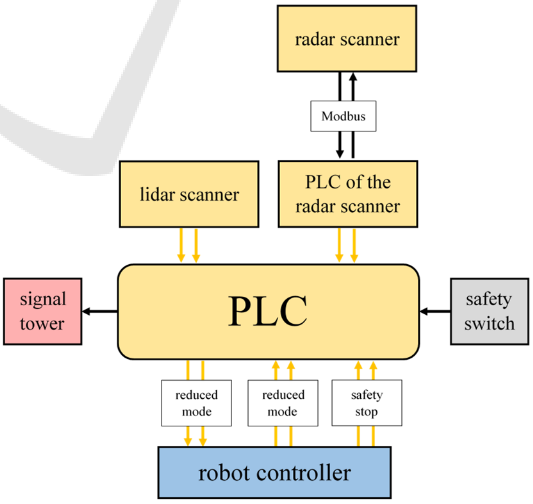

Figure 5: Configuration of the external sensor system by the PLC.

The robot controller is also communicating with the PLC, when the robot is either running in the *reduced mode* or stands still, because of a *safety stop*.

Generally, the *reduced mode* can be triggered by the external safety system as well as by the internal safety system through configured protective levels on the robot. The safety status of the robot is signalized by the signal tower, so that the worker gets feedback even if they are not right next to the robot cell. The safety switch can be used to switch off the external safety system so that the robot is continuously running in the *reduced mode*.

4.4 Entire External Safety System

As shown, the safety distances need to have a minimum size to detect a human reliably to the front and to both sides. Figure 6 shows the entire safety space of the external sensors.

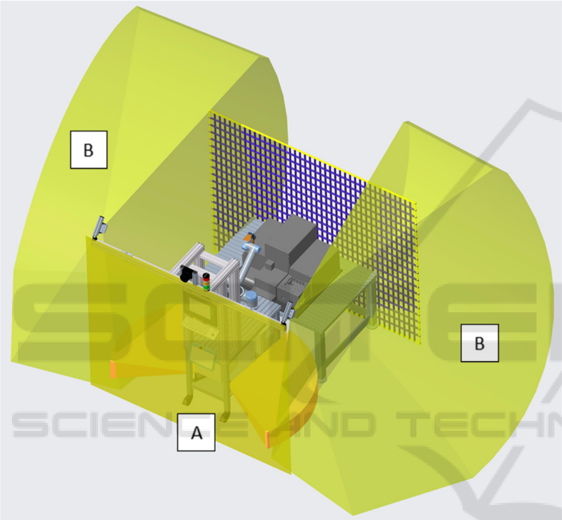

Figure 6: Supervised area of the entire external safety system.

Behind the workplace a safety fence prevents a worker from entering the robotic cell. In our research, we distinguish between two different constitutions of the space, where the robotic cell is supposed to be set up. First, the *inappropriate space*, when there is not enough space nearby the real industrial workplace for the supervised area by the external safety system. In this case, the safety distances can not be maintained and the sensors are continuously triggered by humans working next to the robot. Subsequently, the mobile robotic cell has to run without the supervision by the external sensors and is set to the *reduced mode* by the safety switch. Second, we considered the so called *sufficient space*. In this case, there is enough space for the supervised area of the external sensors, which means that workers nearby the robot do not continuously trigger the sensors. Thus, the robot can run with maximum speed and force and is only switched to *reduced mode* when a human is entering the robotic cell, for example during a change of the box for the supply and removal of components.

The external safety system is not limited to one Cobot size. When a bigger robot is used there are not more sensors needed. When the reactivity of the bigger robot is different to the current Cobot, either the angle of the sensors mounted on the mechanical structure can be adapted or the safety planes can be moved to hold the safety distance according to the standard. There is no need to add more sensors.

5 INTERNAL SAFETY SYSTEM: SAFETY PLANES AT THE ROBOT

The safety system also uses the internal sensors of the robot to transfer the robot into the *reduced mode* and to limit the movement area of the robot. In our research, we configured and tested so-called safety planes at the robot that are presented in the next sub-chapters.

5.1 Initiate the Reduced Mode

The *reduced mode* is initiated, when the robot is crossing predefined safety planes to the front and to both sides, as it is illustrated in Figure 7.

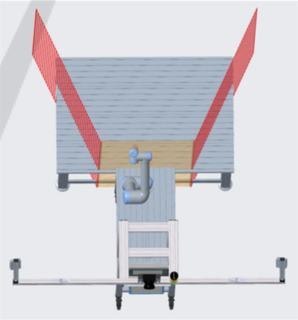

Figure 7: Safety planes to initiate the reduced mode.

When the robot moves back inside the curtailed area, it is set back to the *normal mode* and moves with maximum speed. Those planes are necessary to minimize the supervised area by the external safety system. The angle of the planes to the side is the same as the angle of the radar sensors that are supervising the space next to the robotic cell. Thereby, the safety distance $S_{min,Radar}$ can be maintained.

5.2 Limiting the Movement Area of the Robot

In order to integrate the flexible safety system in a real semi-automated production line, the robot´s movement nearby the head and face of a human has to be limited. According to the DIN EN ISO 14738 (DIN Deutsches Institut für Normung, 2009) the standard height of the shoulders including the heel of the safety shoes is 134 cm. Therefore, the safety plane at the robot is configured parallel to the ground at this height. It is not initiating the *reduced mode* but is limiting the movement area of the robot to the top. Respectively, the Tool-Center-Point (TCP) is not able to cross it.

6 STANDARDIZED CE-MARK

To fulfill the requirement that no individual safety assessment has to be performed on a new workplace, we defined criteria to classify a specific component series. The biggest (95x145x50mm) and heaviest (536g) part of the series shows Figure 8.

Figure 8: Component from DEHN SE + Co KG.

The rest of the series consists only of three, two or one chamber. By the definition of the criteria, also other parts that looks completely different can be handled without the performance of an individual safety assessment. The only precondition is that the considered application is not accessible from behind the workplace and the new components correspond to the specification in Table 2.

Table 2: Classification of a component series for a standard CE-Label.

Criteria	**Limit**
Basic form	Cuboid
Sharp forms that are emerging out of the geometry	Not existing
Size of chambers	Max. 32x45mm
Mass	Max. 536g
Length	Max. 250
Width	Max. 250
Height	Max. 250
Corner radius	Min. 0,5mm
Edge radius	Min. 0,5mm
Sharp edges/corners	Not existing
Surface condition	Rz < 1mm

Next to the definition of the criteria, we also constructed and 3D-printed a safe vacuum gripper that is able to handle the components of the series. It consists of two suction devices that can be flexible removed and added to the housing of the gripper. Finally, the gripper must not be changed at a new workplace with new parts, so that the safety assessment and the assignment of a CE-mark is made much easier.

To verify our safety system, we also performed an extensive assessment of risk with the biggest and heaviest part by using the software SafExpert. The application we considered was from a project partner of AdhocMRK. In this case, presorted parts from a box are picked by the robot and inserted into an automatic test machine. After the successful high potential test, the parts are removed and sorted into another box next to the robotic cell.

Most of the risks could be eliminated by an inherent safe construction. For the rest of the risks we performed a force and pressure measurement according to ISO/TS 15066. By evaluating 40 measurements, we were able to define the safe speed of the robot by 200 mm/s. That is the speed for the robotic cell, when it is running in the *reduced mode*.

7 VALIDATION OF THE SAFETY SYSTEM

In our research, we also performed the validation of the flexible safety concept with the radar sensors to check and confirm the functionality of the system as following:

- Verification of speed regulation and sensor activity
- Cycle time measurements for the safety planes
- Adaptability for different workplaces

First, we evaluated and confirmed the functionality of the implemented safety concept with the described safety functions. Therefore, we first verified the positions and range of the supervised areas by the external and internal sensors. We were both entering the robotic cell from several sides and moving the TCP of the robot from inside in direction to the supervised areas and the safety planes. We checked the signal for the reduced mode with the signal tower and the safe digital outputs for the *reduced mode* on the robot controller for several positions.

Second, in order to analyze the influence of the variation of the safety planes position on the cycle times, a prototypical application was examined. When the robot is crossing the planes, it is transferred to the *reduced mode.* Figure 9 shows the experimental setup for the time measurements:

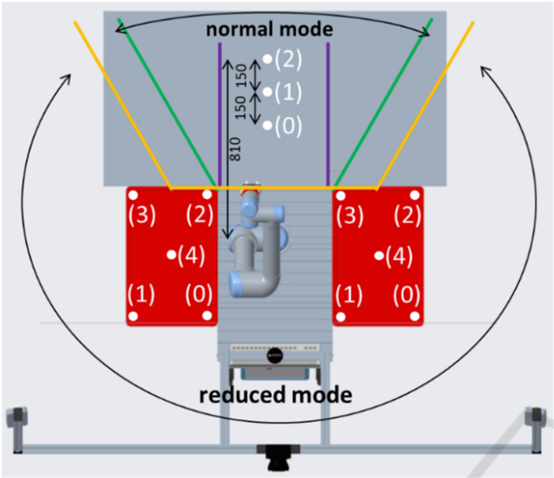

Figure 9: Experimental setup for the variation of safety planes position and time measurements.

The robot is moving cyclic from position (0) of the left box to position (0) on the table, which characterizes the workplace, to position (0) of the right box. Thus, the path would be (0, 0, 0). In the next cycle, the robot starts again from (0) of the left box, to (0) of the table and to (1) of the right box. So the entire sequence would be from (0, 0, 0) to (0, 0, 4), continued with (0, 1, 0) to (0, 1, 4) and so on. The last cycle is from (4, 2, 3) to (4, 2, 4). Finally, the robot was driving to every position from the left box, combined with every position on the table and every position from the right box during one sequence. All the positions were sent to the robot via a TCP/IP socket connection between a computer and the robot controller. The time was measured for each cycle by a C#-program and saved to a .csv-file for evaluation. Overall, we recorded three sequences, which contain of 75 cycles each. Every sequence is representing one configurations of the safety planes. In summary, we evaluated 225 cycles. The longest cycle times expected to be from point (1) of the left box to all the other positions of the table and the right box, because it is the longest path of the robot. Thus, this point is considered for the evaluation. According to that, the robot performs five cycles crossing each of the three points on the table (0, 1 and 2), which results in 15 measurements. In *normal mode,* the robot drives with a speed of 400 mm/s, which is performed mostly nearby the table. When the robot is crossing the planes, it is only moving with 200 mm/s. Figure 10 shows the result of our cycle time measurement:

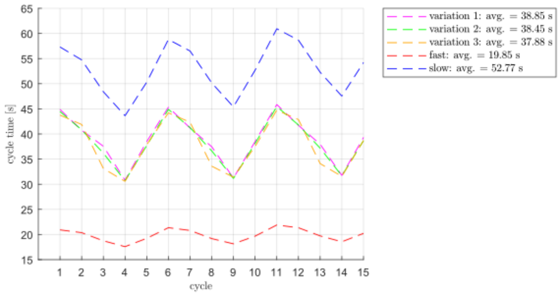

Figure 10: Evaluation of the cycle time measurements.

Next to the transition from normal to reduced mode by the different safety plane configurations, we were also testing the robot continuously running in the normal (fast) and the reduced mode (slow). Our experiment shows that the position of the safety planes has no significant influence on the cycle times (variation 1-3). The average value differs only by 1.4 s. The speed of the robot is most essential, respectively the speed in the *reduced mode.* This has the biggest influence.

Third, we recorded and compared the time the radar systems needs to adapt to new workplaces. When a new object is added to the supervised area of the sensors, a new workspace is created. In this case, the sensors have to be initialized and adapted to the new environment. This is done automatically by the sensors and can be monitored by the safe two-channeled digital outputs of the controller. When the environment changes, the digital outputs stay FALSE until they are finally initialized and switched to TRUE. A timer, which has been programmed on the robot controller, supervises the digital outputs and determines the time of initialization.

To create new workspaces in the laboratory, four boxes of different sizes were selected (30x20x150, 40x30x220, 600x400x120, 600x400x320mm) and set up with varied combinations on a table next to the robotic cell. The latter is inside the supervised area of the radar sensors. These boxes are standardized according to VDA 4500 and are most commonly used in the automobile industry and for high-automated production processes. The number and size of the boxes define the complexity of the combinations. The higher the number and the bigger the size of the boxes, the higher the complexity. In our set up, we distinguish between four grades of complexity: low, medium, high and very high. Figure 11 illustrates the results of the initialization measurements for different workplaces:

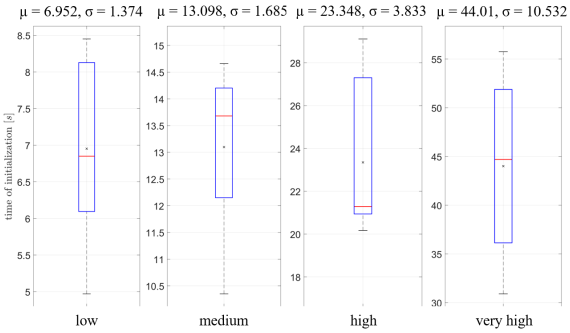

Figure 11: Time of initialization with different complexities.

The median, which is represented by the red horizontal lines, show that the smaller the change in the scenario compared to the previous one, the faster is the time of initialization. The interquartile range (IQR) differs from 2 s (low), to 2.2 s (medium), 6.3 s (high) and 15 s (very high). Therefore, the higher the complexity the higher is the variance for the time of initialization. Nevertheless, the measurements show that the highest recorded time was 55 s. When a worker is manually configuring the sensors at a new workplace, e.g. a laser scanner to both sides instead of the radar sensors, the time would be considerably longer.

8 CONCLUSION

In summary, we presented a safety system that can be flexibly used for different real industrial applications. Because of the specific feature of the radar sensors, no individual configuration is necessary, when the mobile robotic cell is set up on a new workplace. Furthermore, all the sensors to supervise the workspace of the robot are mounted on the mobile platform. This makes it easy, flexible and fast to be integrated in an existing production line, because no workplace has to be adapted. We also presented a first approach to achieve a standardized CE-mark for a component series. The laser scanner at the front also reduces the supervised space in front of the robotic cell. The advantage is that workers walking by via a footway do not trigger the safety sensors. The entire safety system has a high flexibility and mobility, because it is usable on different workplaces with different surrounding without an individual safety consideration and without the adaption of configured safety planes and safety areas of the radar and laser sensors. The presented solution is usable in a real industrial surrounding for the entire e-series of Universal Robot, but is not limited to those Cobots. Most of the Cobots have the possibility to program safety planes that transfer the robot to the reduced mode. Nevertheless, to improve the efficiency and the usage of the presented safety system, more testing with different Cobots is necessary.

For further research, the sensitivity level of the radar sensors (normal, high, very high) in relation to the speed and acceleration of the robot is supposed to be analyzed. When the robot stops too quick or accelerates too fast, the sensors mounted on the framework are triggered, because of small vibrations on the mobile cell. To avoid the undesired triggering of the radar sensors and to reduce the cycle times more research is necessary.

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