Safeguarding and supporting future human-robot cooperative manufacturing processes by a projection- and camera-based technology

Christian Vogel\textsuperscript{a,}\textsuperscript{*}, Christoph Walter\textsuperscript{a}, Norbert Elkmann\textsuperscript{a}

\textsuperscript{a}Fraunhofer Institute for Factory Operation and Automation IFF, Sandtorstrasse 22, 39106 Magdeburg, Germany

Abstract

This contribution aims in presenting a projection- and camera-based technology that provides not only the safeguarding of humans but also capabilities for supporting and assisting the human in human-robot cooperative manufacturing processes. The proposed technology establishes dynamically generated safety spaces by directly projecting them into the shared workspace thus separating human and robot. Besides the safety aspect the proposed “speed and separation monitoring”- technology also allows the visualization of arbitrary information as well as interaction functionalities with the robot, process or system. This technology and its beneficial functionalities will be presented on basis of an industrial demonstrator featuring a screwing application.

Keywords: Safety, Human-robot cooperation, Workspace surveillance, Industrial robot, Optical safety system,

1. Introduction

The International Federation of Robotics (IFR) [1] forecasts that the number of newly installed industrial robots will reach 1.4 million by 2019. With this increase of robots in industrial automation, the demands for human-robot cooperative workplaces are also set to rise. Manufacturing processes that allow concurrent work of humans and
robots in a shared environment require that the human is safeguarded at all times. But in future industrial manufacturing the hard-safety aspect won’t be the only requirement to such cooperative workplaces. Soft-safety, interaction functionalities and worker assistance will contribute to an overall flexible and innovative human-robot workplace.

For monitoring human’s safety we can differentiate between two approaches. The first one generally permits contacts between human and robot but it ensures that the arising forces are below the accepted thresholds. This “power and force limiting” – approach is used to design collaborative robots like KUKA iiwa [2][3], the Universal robot [4] or Fanuc CR-35iA [5]. Besides these cobots there are sensory developments existing that enable industrial robots for safe human-robot collaboration. Pressure sensitive sensors are used to enclose the robot like an artificial skin to detect and to cushion collisions between human and robot [6][7]. Further developments are used to observe the nearby environment to detect objects in close proximity of the robot. Such sensors like ultra-sonic sensors or capacitive sensors are directly attached to the robots surface and may lead to a reduced robot speed or entire motion stop at object detection [8][9][10]. But, all of these solutions are only practical for small or mid-sized shaped robots and they require additional safety systems for monitoring additional tools and workpieces at the robot.

Safety systems that consider the entire robot system with tools and workpieces are following the concept of “speed and separation monitoring”. Potential collisions between human and robot are detected in advance and can be avoided by particular reaction strategies of the robot. The optical sensor systems are mounted stationary in the environment for monitoring the robot’s workspace and can consist of several camera combinations and configurations [11][12][13]. On basis of the camera’s data the current distance between human and robot is determined which is further used to initiate a motion stop, speed reduction or trajectory adaption of the robot. A safety-certified monitoring system based on stereo-camera techniques is already commercially available by Pilz [14]. However, a main drawback of these optical sensor systems is whose dependency on environmental light conditions. Furthermore, the human is not aware about the separation distances that are actually monitored by the safety system. Unintended violations of the safety spaces by the human lead to a decreased availability of the robot and the entire system.

The main benefits of the proposed projection- and camera-based approach for workspace surveillance are the reduced dependency on environmental light conditions, intrinsic safety, high potential for safety certification and overall valuable functionalities. Here, the capability of providing virtual interactive buttons that allow the control of robot (start/ pause motion), system (choose/ manage task) and process (confirm production step) offers an intuitive communication. Besides interaction, the system also offers the visualization of safety-, robot- or process-specific information by projecting them directly into the shared workspace to support the human at work, configuration-time, and even for failure diagnosis.

2. Projection- and camera-based technology

The projection- and camera-based technology is capable of establishing safety spaces of arbitrary shape, size and position directly into the shared workspace of human and robot. By connecting this safety system to the robot’s controller, the safety spaces can be dynamically generated on basis of the robot’s joint angles and velocities. Here, the approach formula described in ISO/Ts 15066 is used to calculate the safety distances that will form a minimal safety hull enclosing the robot at any time. The safety system incorporates the calculated safety hull to generate and emit a border in the form of a line (i.e. the border of the safety zone) that separates the human and robot. If this projected line is disrupted by an object such as a human’s hand or fingers, the surrounding cameras recognize this safety space violation robustly. A safety space violation results in the reduction of the robot’s speed or even an immediate robot stop. From the perspective of the human co-worker, it is generally advantageous to be aware of the current safety space, giving them the possibility of actively avoid safety violations. This will lead to an improved availability of the robot and the overall system as well. Visualizing additional symbols, for instance, to represent intended robot movements will further enhance the user acceptance.

In the following we will describe in detail the operational principle of the projection- and camera-based technology. Afterwards we present the possibilities of using this technology as an interaction and visualization system to allow an easy and intuitive communication between human and robot.
2.1. Operational principle of safety function

The entire operational principle of the proposed technology is based on projector and camera techniques. While the projector emits the light to the projection surface (i.e. workbench) the cameras receive the reflected light rays as depicted in figure 1a). Here, the projector emits a small bunch of light rays for visualizing a spot on the projection surface that is viewed by a single camera. In this basic embodiment the operational principle of the technology is similar to them of a light barrier.

![Figure 1: Operational principle of projection- and camera-based technology providing safety function.](image)

For using the technology as a safety system for safeguarding humans in human-robot cooperative applications we need to robustly and reliably detect disruptions of the light rays emitted by the projector. Here, we must differentiate between two cases. One case concerns the situation while an object disrupts the light rays before reflectance by the projection surface. The other case handles the situation when an object disrupts the light rays after reflectance by the projection surface. Here, the light rays can be either interpreted as reflected light rays of the projector or appropriate view rays of the camera. As it is depicted in figure 1b) the camera’s perspective view to the projected spot is occluded by an intruding object that results in non-recognition of the projected light. For detecting this kind of object intrusion we have to determine reliably the lack of emitted light rays in the camera image.

In the second case the object disrupts directly the emitted light rays of the projector as shown in figure 1c). In contrast to the first case the camera indeed recognizes emitted light rays of the projector but at incorrect image positions. A reliable detection of this kind of object intrusion requires a robust position determination of light rays in the camera image as well as a specification of pixel positions in the camera image at which the light rays are expected. In summary, for robustly detecting objects disrupting either projector’s light rays or camera’s view rays we have to answer the following two questions:

- At which pixel positions in the camera image do we actually recognize the reflected light rays?
- At which pixel positions in the camera image do we have to recognize the reflected light rays in an undisrupted case?

For answering the first question we have to develop a method that allows a differentiation between the projected light and the entire environment that are actually viewed by the camera. On basis of one camera image it is hard to differentiate between the light rays of the projector and the light rays of additional light sources in the environment. Especially the dynamics in changing light conditions doesn’t allow a reliable determination of the emitted light rays. To overcome this challenge we implemented a method that uses two camera images acquired alternately at operation. As the first image is acquired at a point of time at which the projector emits light, the second image contains no emitted light of the projector. These two camera images differ only in areas where the camera recognizes the emitted light of the projector. These areas can be easily and robustly extracted by means of difference computation. The resulting binary image specifies the current pixel positions of the extracted light rays and is called current state mask (see figure 2). As the points in time of image acquisition are close together the changes in environment are very slight and do not negatively affect the process of light ray determination. Thus, the influence of changing light conditions like shadows and additional extraneous light sources to the extraction process is reduced significantly. For achieving almost independence concerning environmental light conditions we further equipped the cameras with bandpass filters that coincide with the wavelength range of the light emitted by the projector. Thus, most of the entire environmental light is filtered except for the light of the projector.
As aforementioned, the extraction process of the projected light rays in the camera image is based on two consecutive images, where one image contains light rays and the other one not. For the implementation of this method we need an exact synchronization between projector and camera. The camera needs to be alternately triggered at times the projector emits and not emits the light. We solved this issue by the development of a trigger-electronic that incorporates the emitting frequency of the projector’s LEDs to generate an activation signal for the camera’s exposure.

But, knowing the pixel positions of light rays in the camera image is not sufficient for determining a disruption of the light rays as depicted in figure 1c). So, it is not clear whether the pixel positions of the extracted light rays are correct or not. To validate them we need the pixel positions of the light rays at which they should be in an undisrupted case. For this, we developed a method that generates a so called expected state mask which is a virtual camera image defining all pixel positions at which the projected light rays must be located (see figure 2). This expected state mask is determined on basis of the extrinsic and intrinsic parameters of the camera as well as the current safety space configuration. A safety space is configured by its 3-dimensional position, size and shape with respect to a common world coordinate frame. For generating this ideal virtual camera image, we also have to consider obstacles that may occlude the camera’s view to areas that contain projected light rays. Here, we use an internal environmental model that comprises all static and dynamic objects in the workspace like robot, tools, workpieces and common items.

On basis of the current real positions of the light rays in the camera image (i.e. current state mask) on the one side and appropriate expected positions of the light rays on the other side (i.e. expected state mask) a match/ mismatch between them can be easily determined. If all of the expected pixel positions coincide with the real pixel positions, there is no safety violation existing (see figure 2). So, if an object disrupts either the light rays of the projector or the view rays of the camera, particular positions of the expected state mask mismatch with the corresponding positions in the current state mask. This situation results in a positive safety violation signal. Moreover, a safety violation is also signaled if projector or camera are not working proper (e.g. defect or error) or if they are decalibrated (i.e. not further adjusted). In these cases a subset (or all) of the defined pixel positions in the expected state mask do not coincide with the appropriate pixel positions of the current state mask, thus resulting in a positive violation signal as well. Generally, the operational principle is based on a closed-circle principle that will signal a safety violation in any case when a mismatch between current state mask and expected state mask is determined. The projection- and camera-based technology meets all requirements to an intrinsic safe system thus ensuring the correct operation of all components at any time.

![Figure 2: From perspective of one camera: Generation of current state mask (3rd picture) by using light image (1st picture) and dark image (2nd picture). Determination of safety space violation by using current state mask (grey wide line) and expected state mask (white thin line) with no safety violation (4th picture) and detected safety violation (5th picture).](image)

A safety space configuration can be defined either manually at setup time before operation or even dynamically depending on internal or external states at operation time. For generating safety spaces that enclose a robot minimally during motion, we connected the robot controller to the proposed monitoring system and implemented a method that generates dynamically the safety space configuration on basis of the current robot joint angles and velocities. These safety spaces meet the requirements to the approach formula that is described in ISO 15066. This formula defines the computation of distances that are used to separate human and robot safely. So, the proposed safety system complies with the “speed and separation monitoring” approach in human-robot cooperative applications. The safety space that needs to be monitored is established in the form of a borderline that encloses the robot minimally. This borderline is adapted dynamically on basis of the current joint angles and velocities anytime. If the system detects the intrusion of an object like human’s finger or hand the robot stops. But, the resulting reaction of a detected safety space violation depends on the application and its corresponding risk analysis.
2.2. Interaction capabilities and information visualization

Besides providing human’s safety in human-robot enabled workplaces the projection- and camera-based technology offers also interaction capabilities that allow an intuitive communication with the system, process or robot. The proposed system allows the definition of virtual buttons that can be established at particular positions in human’s environment. The size, shape and position of these buttons can be defined individually and may depend on the application or user’s preferences.

In general, the operational principle of these interactive buttons is based on the method of safety space generation and monitoring as previously explained. But, in contrast to safety spaces, the detection of an intruded object will not lead to a stop (or motion speed reduction) of the robot but to a user-defined reaction. That is, the human may control the robot (e.g. pause motion), choose the next task or confirm finished processes by ‘pressing’ these buttons. Moreover, these virtual buttons can be changed in functionality and position with respect to the current human’s task or robot state. This allows a user-centered design of the entire application and enables the human to control and interact with the manufacturing process in a new manner. The results of these interaction capabilities are improved user acceptance and ergonomics.

As we described the human’s possibilities to interact with the system, process or robot, the communication directed to the human is just important as well. Here, we use the projection- and camera-based technology to support and assist the human at work by visualizing relevant information directly into the user’s workspace. In general, the system may inform the user regarding process-, robot- or safety-specific states. In the first case the system helps the user fulfilling the current task by visualizing beneficial information. This may be some kind of pictograms, schemes or textual representation. The system can also highlight particular areas that are of special interest and can give some hints for next process steps. In case of error and fault diagnosis the system can visualize information to manage and solve the issue. This concerns even the robot. Besides presenting information regarding the current state of the robot, intended robot movements or next actions like grasping can be also displayed. An increased user awareness of the current robot’s state and its intention lead to a higher user acceptance of working side-by-side with the robot. The visualization of safety-specific information directly affects the availability of the robot and system. When the user is aware of current safety space boundaries, unintended safety space violations can be actively avoided. Besides presenting the current safety space border, the system additionally depicts marks or signs to indicate the safety-critical area. In summary, information visualization affects the user’s awareness and improves the user’s acceptance.

3. Human-robot cooperative manufacturing process

The cooperation of human and robot combines the strengths of both improving the flexibility and efficiency of the manufacturing process. Besides the safeguarding of the human such human-robot shared workplaces require novel and innovative technologies that allow a support, communication and interaction between human and system/process/robot. In the following we describe a human-robot cooperative workplace that features a screwing application. We present the possibilities and benefits of using the projection- and camera-based technology for safeguarding, information visualization and interaction.

3.1. Workplace setup and Screwing application

The human-robot cooperative workplace has a dimension of about 1.10 meters by 2.00 meters and is divided into two areas (see figure 3). The “robot-area” is surrounded by fences on three sides and the access to this area is only permitted for the robot. The “shared-area” is accessible by human and robot simultaneously, thus this area needs the safeguarding of the human while the robot is in operation. That is, human and robot are safely separated and physical contacts between them are not allowed. The safeguarding of the human is provided by the projection- and camera-based technology that’s techniques are mounted in a height of about 1.40 meters above the workbench. The system consists of one projector and two cameras that are adjusted as shown in figure 3. The modular buildup of the structure allows an easy adaption of the perspective views of the components. The length and orientation of the tubes can be adjusted individually according to the requirements of the application.
The LED-DLP projector features HD-resolution and is synchronized with the cameras by additional trigger electronics. The industrial-grade cameras offer a framerate of about 50 Hz with a resolution of 780 by 560 pixels. With this setup the system is able to robustly detect objects with a minimal diameter of 10 millimeters that are intruding into the safety space. The industry-oriented screwing application consists of two individual steps, a manual one and an automated one. The workpiece consists of a ground plate and several mounting plates that need to be fixed altogether. The first task comprises both the manual assembly of the mounting plates with the ground plate and the manual insertion of the screws into the corresponding holes of the mounting plates (see figure 3).

This preparation task of the workpiece is done by the human co-worker. The second task concerns the fixation of the screws by a defined tightening torque. Here, we use a KUKA iiwa 14kg robot that was equipped with an electric screwdriver that can be activated and deactivated by software (see figure 3). After locating the positions of the screws the robot touches them with the screwdriver by using its sensitivity feature. While the screwdriver is active the robot moves downwards to tighten the screws. The desired tighten torque is accomplished by the screwdriver.

3.2. Maintaining human’s safety

While the human prepares the workpiece by assembling the mounting plates and inserting the screws, the robot waits safely in home position. As the human finishes the preparation of the workpiece the robot can start executing its task. According to a hazard and risk analysis, we have to maintain human’s safety at all times the robot is in motion to avoid collisions between human and robot. Furthermore, we have to monitor the robot’s processing of the screws due to the hazards that might arise from clamping and rotating screws respectively screwdriver.

The proposed projection- and camera-based technology is used to avoid these potential hazards that result by robot’s operation. Altogether we implemented three safety spaces that can fuse to one comprehensive safety space depending on the application’s sequence. The first safety space separates the “robot-area” from the “shared-area” and interconnects the two ends of the fence that result in a continuous safe enclosing of the robot without any interruption. This safety space guarantees that no object, human’s hand or fingers can intrude into the “robot-area” because of the seamless transition between fence and safety space (see figure 4, first picture).

According to the risk analysis we also have to consider the workpiece in our safety concept to guarantee human’s safety while the robot respectively screwdriver is tightening the screws. For this, we introduced another safety space that encloses the workpiece entirely. The position of this safety space is adapted according to the actual position of the workpiece.
The third safety space encloses the robot minimally at motion and is based on the current robot’s joint angles and velocities. The system incorporates the robot’s state to determine the minimal safety distances that are necessary to separate human and robot. These safety distances are computed with regard to the approach formula described in ISO TS 15066. While the robot moves towards the workpiece all three safety spaces are fused to an overall comprising one as depicted in figure 4, pictures 3 – 5. The fusion of safety spaces ensures that there is no possibility to intrude into the “robot-area”. In conjunction with the fence, the safety spaces will form a closed guard around the robot, tool and workpiece at any time.

A disruption of the established safety spaces by human’s hand or fingers lead to an immediate stop of the robot. In addition, if the safety space is violated while tighten the screws then the screwdriver stops operation. Thus, the potential hazards identified by the risk analysis could be reduced to a compliant minimum (see figure 5).

3.3. Support, worker assistance and interaction

Besides the safety aspect of the projection- and camera-based technology this system additionally allows a communication, assistance and interaction between human and robot as explained in section 2.2. So, we implemented particular visualizations and interactive buttons as well as an assistive area to help and support the human at work. In figure 6 the “shared-area” of the workplace with additional projected items is depicted. The front area (1) is used to establish the interactive buttons that allow a control of the robot. Area (2) provides user-assistance for the preparation of the workpiece by the human. Beside these areas we present some textual messages that can be used to describe the current process or give some task-related hints (3). While the human prepares the workpiece by assembling the mounting plates the system tracks the workpiece and visualizes beneficial information. Further on, we implemented a user-dependent control of the robot/ process that provides particular interactive buttons. The user’s identification is determined by a marker-based id card. The interactive buttons allow a start/ pause and break-off of the robot’s motion.
Conclusion

In this paper we presented an innovative technology for monitoring human-robot enabled workplaces to ensure the safety of humans. Besides the safeguarding of the human coworker, this projection- and camera-based system provides additional beneficial functionalities like worker assistance and interactive communication. We presented the benefits of this technology on basis of an industry-oriented manufacturing process that features a screwing application.

Acknowledgements

This research was partly supported by the FourByThree project that has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 637095.

References


Figure 6: Left: Shared-area of the human-robot enabled workplace comprising an interactive area (1), area for user-assistance (2) and textual description for process- or system-related hints (3). Mid: Assembly of the workpiece with additional information visualization. Right: User-dependant presentation of particular interactive buttons to control the robot and system.