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Review of vision-based safety systems for human-robot collaboration

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Abstract

Safety in human-robot collaborative manufacturing is ensured by various types of safety systems that help to avoid collisions and limit impact forces to the acceptable level in a case of collisions. Recently, active vision-based safety systems have gained momentum due to their affordable price (e.g. off-the-shelf RGB or depth cameras and projectors), flexible installation and easy tailoring. However, these systems have not been widely adopted and standardized. The vision-based commercial products can only be found in a limited number. In this work, we review the recent methods in vision-based technologies applied in human-robot interaction and/or collaboration scenarios, and provide a technology analysis of these. The aim of this review is to provide a comparative analysis of the current readiness level of vision based safety systems for industrial requirements and highlight the important components that are missing. The factors that are analysed as such are use case flexibility, system speed and level of collaboration.

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Keywords: human-robot collaboration; manufacturing; safety; industrial robots; monitoring; classification

1. Introduction

During the past few years human-robot interaction (HRI) and human-robot collaboration (HRC) have gained a vast amount of interest among researchers and industry world wide. In order to increase the flexibility and changeability of assembly processes, more advanced interaction and/or collaboration between the operator and the automated assembly system is required. The interaction between human and robot is expected to improve assembly processes, particularly in workplace-sharing collaboration, where a robot can be guided by a worker and the robot provides power assistance to the worker [17,18]. In this scenario, perception, efficient reasoning and safe collaboration between humans and robotic systems are key components for increasing efficiency in production. It is expected that in future semi-automated robotized assembly requires industrial robots to collaborate with human workers as part of a team to complete tasks based on their individual competences [1].

When developing and implementing the HRC, the safety of the human should be the first thing to consider. To avoid collisions in a shared workspace, the position of the human has to be known in real time. Furthermore, the moving trajectory of the human and speed of movement has to be assessed continuously. The directives and national occupational safety laws require well-designed and safe interaction. This increases the productivity and work efficiency. It has to be noted, that mental workload occurs even though safety features have been ensured in the system. This influencing factor can greatly affect the productivity [37].

Recent standards on robot safety provide requirements and guidance how to maintain safety during interaction between humans and industrial robots. The International Organization for Standardization (ISO) 10218-1/2 [14] outlines some methods of safe collaborative work and ISO/TS 15066 [15] supplements it and provides additional guidance for safety in human-robot interaction. However, the standards leave many issues still ambiguous. For example, how to define the required safety functions and which human features (whole body, gestures, face, readiness, etc.) should be precisely detected [4].

Safety of humans in HRI can be ensured by different strategies and methods. Lasota [20] divides safe human-robot interaction into four methods: safety through control, safety through motion planning, safety through prediction and safety through consideration of psychological factors. Safety through control include pre- and post collision control methods. In pre-collision the methods prior to contact between a human and robot are considered. The safety is ensured by preventing collisions by using methods including defined safety regions, tracking separation distance, and guiding robot motion away from humans. Post-collision methods aim to minimize injuries when a collision is detected. The target of safety through motion planning is to plan safer robot paths and motions in order to avoid collisions. Safety through prediction involves predicting human ac-

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tions and motions. Safety through consideration of psychological factors aims to ensure that interaction remains stress-free and comfortable for the human.

To avoid collisions in HRC, location of the human and often location of his/her limbs have to be known reliably and in real time. Two methods to detect human and limbs have been widely considered in literature: vision based methods and inertial sensor based methods using a special suit for motion capture [8]. The latter approach may not be considered as a realistic solution for real applications because of the need of wearing a special uniform with sensing devices and insufficient detection of movement in the environment around the human [27]. Leaving objects in the workspace and objects carried by a human unsupervised may lead to dangerous situations. Although vision based safety in HRC is widely studied, availability of commercial and standardized vision based safety sensors is still very limited. Most common is SafetyEYE [29] which enable to configure multiple safety zones for the human-robot workspace. The system monitors the violations of these predefined zones and forces the robot, e.g. to decrease the speed or stop when movement is detected in a certain zone.

In this literature review and technology analysis, we focus on vision based safety technologies and methods to detect humans and objects in the workspace and avoid collisions in interaction and/or collaboration between the human and the robot(s). The review is divided into two chapters; the state-of-the-art in HRI and HRC safety (Section 2), and the state-of-the art of vision based methods (Section 3). In Section 4 we discuss the challenges identified in these vision based systems. Section 5 concludes the work and gives future directions.

2. Standards, guidelines and strategies for safe human-robot collaboration

The ISO 10218-1/2 [14] standards give safety requirements for robots and robot systems. The collaborative operation between a person and a robot sharing a common workspace is also handled. Technical specification (TS) 15066 [15] provides additional guidance for safe HRI. The standards define four collaborative operations. First, *safety-rated monitored stop*: when a human is inside the collaborative workspace, the robot is not allowed to enter this area. If the robot is working inside the collaborative workspace and a human enters this area, the safety-rated monitored stop is activated. Second, *hand guiding*: a special hand guiding device, integrated to the robot end effector, allows a human operator to guide the end effector to a desired location. Also in this method, when the person enters the collaborative workspace then the safety-rated monitored stop has to be activated. Third, *speed and separation monitoring*: the safety is ensured by maintaining at least the protective separation distance between a human and the robot at all times. The slower the robot speed is, the smaller separation distance is allowed. If the separation distance decreases below the protective separation distance, the robot has to stop. Fourth, *power and force limiting*: physical contact between human and robot system is allowed. In this method, the risk reduction is done by keeping the hazards related to robot system below threshold limit values that are defined in the risk assessment. Marvel [23] proposed a set of metrics to evaluate speed and separation monitoring efficacy in shared workspaces in an industrial environment. More recently, Marvel and Norcross [24] provided guidance for implementing speed and separation monitoring in collaborative robot workcells.

Several authors have provided their guidelines and strategies for safe HRC that are aligned to today's standards or could be aligned with expected future standards. Bdiwi et al. [4] introduced a new classification strategy depending on the level of interaction between a human and a robot in a shared workspace. Furthermore, they proposed required safety functions and defined which human features should be detected and which robot parameters should be monitored or controlled at each level of interaction, taking into account the ISO standards [14,15].

Matthias et al. [25] introduced a safety concept with seven levels of safety. Their approach showed in a simplified manner how the most relevant risks could be assessed and reduced to be harmless by the cumulative risk reduction effects of the measures applied. Bdiwi et al. [4] defined four levels of interaction. In *Level 1*, the human works near the robot but they each have their own tasks. The shared fenceless workspace is divided virtually into human and robot zones. The robot is not allowed to enter the human zone and if a human enters the robot zone, the robot is stopped. The human zone is static and the robot zone can be either static (robot can move only in limited predefined zone) or dynamic (the zone can vary depending on the robot motion). In *Level 2*, the human and the robot have a shared task without physical interaction. In addition to human and robot zones, this level has a cooperation zone where the robot decreases its speed according to the distance to the human. In this level, the robot can assist the human as a third hand, for example, by holding a component firmly and stationary while the human is performing an assembly task. In *Level 3*, the human and the robot can have a shared handing-over task but the physical interaction between them does not occur. In addition to the zones in the previous levels, a special zone for the handing-over task is defined. In the handing-over zone the robot is controlled in a hybrid control manner, which allows it to react to the motion of the human hand and follow it during the handing-over task. In *Level 4*, the human and the robot have also physical interaction in addition to previous interaction modes. One example of this is when the human guides a heavy component held by the robot to a final position.

In their taxonomic safety function strategy, Bdiwi et al. [4] define several safety functions that may be required in each level of interaction. *Safety-rated monitored stop* is a fundamental safety function that is required at all levels. This function requires to ensure that the distance between the human and the moving robot is always at a permitted level. When the distance gets too short, the robot motion has to be stopped or paused. The objective of the *detection of faulty events* function is to detect human actions taken near the robot. The authors identified several events that can be detected based on visual information; these include linked (human has touched the robot), covered (human has been covered by the robot), parted (human is separated from the physical interaction) and un-covered (human has appeared suddenly far away from the entrance etc.). *Robot position*, *robot speed* and *torques/forces* are functions of the robot's main parameters.

The taxonomy recommends which parameters should be monitored and controlled depending on the interaction level. Robot speed monitoring and control is needed from level 2 upwards. Robot speed control needs the information of distance between the human and the robot, which is a typical application of vision systems concerning safety in human robot interaction. The *near field vision system* function is used for detecting human readiness for action, monitoring the upper body and hand safety and hand gestures in close proximity interaction (in interaction levels 3 and 4). Mohammed et al. [27] proposed four collision avoidance strategies: alarming a human operator, stopping a robot, moving the robot away from the operator, or modifying the robot trajectory at runtime. Wang et al [45] introduced a symbiotic collaboration scheme to classify collaboration stages.

3. Vision-based monitoring and safety systems

3.1. Distance between points and obstacles

Flacco et al. [11,12] presented a fast method to calculate the distance between a number of points and moving obstacles (e.g., between robot joints and a human) in depth space with a depth camera. Later on they extended the method for multiple depth sensors [13]. According to the authors the whole distance calculation algorithm is performed at around 300 Hz. They used the distance to generate repulsive vectors that are used to control the robot while executing a motion task. In their latest paper [13] the authors demonstrated the real-time performance of the method in collision avoidance experiments with a 7R KUKA LWR-IV robot and two Kinect sensors.

3.2. Collision avoidance

Lacevic et al. [19] introduced a kinetostatic danger field concept. To overcome some of the limitations in this approach and earlier work on repulsive potential field approach by [16], Polverini et al. [31] introduced a new concept of kinetostatic safety field, that captures a risk in the vicinity of a rigid body (e.g. an obstacle, a human body part or a robot link). The safety field depends on the position and velocity of the body and is influenced by its shape and size. The method was validated through collision avoidance experiments performed with an ABB FRIDA dual arm robot and Kinect which monitored the human upper body by skeletal tracking [30].

Saveriano and Lee [33,34] proposed a real time vision algorithm for reactive avoidance of moving obstacles. They calculated a dynamical system modulation matrix directly from a point cloud using the distance from the obstacles and their velocity. They validated their approach with simulations and experiments on a 7 DOF KUKA light weight arm and a RGB-D camera. In their experiments the robot was able to avoid collision with a moving obstacle up to speeds of 1.4 m/s (obstacle speed). Wang et al. [44], Schmidt et al. [35,36] and Mohammed et al. [27] have developed an approach for online collision avoidance in an augmented environment where virtual three-dimensional (3D) models of robots and real images of a human from depth cameras are used for monitoring the working area and avoiding collisions. They used a point cloud of a human and a 3D model of the robot to calculate the distance between human and robot. The authors verified the method with a collision avoidance experiment with a simple robot path and a static obstacle as well as hand following experiments where the robot's end effector followed the hand of the operator.

Ahmad and Plapper [1] proposed an approach where a time-of-flight (TOF) sensor mounted on top of the cell is utilized to monitor a peg-in-hole process environment. In this scenario a KUKA robot is working and a human worker or any static object is recognized as an obstacle. In their approach collision avoidance was performed by scheduling or by detecting and avoiding. A specific Robot Path Planning (RPP) algorithm was developed for this scenario.

3.3. Human Intention recognition

Bascetta et al. [2] introduced an approach to human intention estimation by using cognitive vision algorithms in combination with statistical methods. They estimate the probabilities of occupancy of defined areas in the robotic cell in near future. The authors taught the system different human motion patterns for the workspace with subset of the walking trajectories obtained from volunteer experiments. Then, the intention estimation algorithm used the motion patterns to predict human intention in the near future. In their experiments volunteers could take one of few predefined paths and the intention estimation algorithm predicted successfully the path before the human walked first half of the path.

Mainprice and Berenson [22] studied close proximity human-robot collaboration based on prediction of human motion/intent. They generated a swept volume of future motion of a human by querying the probabilistic models learned in the offline phase. Then, the robot motion planner plans trajectories to avoid the collisions between human and robot. They verified their approach with recorded human motions and simulated robot.

3.4. Utilization of multiple sensors and sensor fusion

Tan and Arai [38] reported a triple stereovision system for monitoring a seated operator's upper body by using colour markers on the clothes. In this approach three cameras were used to produce three pairs of stereo vision images to improve the robustness towards lost tracking and occlusion tolerance.

Rybski et al. [32] used sensor fusion for ensuring human safety in close proximity to robots in an industrial workcell. They fused data from multiple time-of-flight (TOF) sensors and stereo cameras to segment the workspace to background, robots, and people. Around each robot they generated an adaptive danger zone and similarly, around each human an adaptive safety zone. When the intersection of danger and safety zone was detected, the robot speed was decreased or the robot was halted. By using the multiple sensors based approach, the authors addressed their work for the main challenges of sensor-based safety systems. These challenges includes occlusions, previously unseen objects due to a complex and dynamic environment and the need for extremely reliable systems that ensure human safety in every situation.

De Luca and Flacco [9] presented an integrated control framework for safe physical Human-Robot Interaction (pHRI) with light weight robots. In the framework, they used first collision avoidance to avoid undesired collisions, but since the collision avoidance could not always be guaranteed, they used a physical collision detection/reaction method based on a residual signal [10]. For the collision avoidance they used a Kinect sensor and a depth space approach [9] to calculate the distance between human and robot. In addition, they used human gestures and vocal based communication for requesting the collaboration from the robot. Also Cherubini et al. [5–7] used multiple sensors for safety in pHRI. They presented [5] a multimodal sensor-based controller that enables a robot to adapt to changes in the sensor signals (e.g. human behavior). The approach was validated in an industrial human-robot collaborative screwing scenario, where positioning, vision (both traditional camera and Kinect), and force tasks must be realized either exclusively or simultaneously [6]. More recently, Cherubini et al. [7] proposed a framework of a human-robot manufacturing cell with direct physical contact between robot and human. In this approach trajectory optimization, admittance control and image processing were utilized. In their system, an industrial 2D camera ensured safety of the operator's hand in a certain assembly phase. If the human hand was detected too close to the robot in that specific phase, the safety stop was triggered.

Bdiwi [3] showed the importance of using different kinds of sensors to ensure human safety during physical interaction with robots. They used vision, force and skin sensors to generate essential information for a robot system during a handing-over task between human and robot. Recently, Bdiwi et.al. [4] introduced a collaboration scenario with heavy duty robots (KUKA KR180) with a payload of 180 kg. Two stereo cameras (S2000 by Intenta) monitored the workspace and a RGBD camera was used as near field vision system. In addition, the robot is equipped with multi-axis force/torque sensor. They reported experiments of a human-robot handing over task that met the requirements of the third HRI level. Four different zones were configured to the workspace; robot zone (danger zone), human zone (safety zone), cooperation zone and handing-over zone. A human operator could move freely in every zone expect for the robot zone. If a human enters the danger zone, the robot stops. If a human enters the cooperation zone, the robot reduces its speed. In the handing-over zone the near field vision system recognized human readiness, upper body and finger safety by detecting face and gestures and tracking the human hand.

Morato et al. [28] presented a real-time (30 Hz) safety framework for close proximity human-robot collaboration by human tracking with multiple Kinect sensors. They replicated human and robot movements inside a physics-based simulation of the work cell. This enabled to generate safe motion goals for the robot through the evaluation of distance between human and robot. Each Kinect sensor outputs a 20-joint human model. The generated human model was augmented by drawing dynamic bounding spheres around human joints, that followed human movements in real time. The robot trajectory was forward-simulated into the near future to create a set postures for the next few seconds. If intersection between future robot postures and bounding spheres of the human model was detected, the robot motion was halted. Morato et al. [28] made experiments to optimize the number of Kinect sensors to maximize coverage in the workspace and minimizing the interference between two neighboring sensors. According to their experiments, four Kinects mounted on the corners of the workspace were sufficient to cover their 3.93m x 2.72m robot working area.

Vicentini et al. [40] discussed implementation speed and separation monitoring safely with non-safety rated sensors and distributed CPUs. The authors showed that it is possible through integration of functional safety methods by using SafeNet [39]. In addition, the authors studied effects of system latencies, inaccuracies and trajectory-dependent robot braking distances on the computation of dynamic speed and separation monitoring. They provide some experimental data of latencies calculated from a setup with COMAU NS16 robot and MESA time-of-flight ceiling-mounted cameras.

3.5. Methods for visualization and monitoring of safety zones

Leso et al. [21] utilized a projector for adaptive placement of virtual optical barriers. The safety line around the 5-DOF manipulator was generated with a projector mounted in the top of the robot cell. The projected line was constantly monitored by 2D vision. The safety stop was initiated if the projected line was interrupted. Vogel et al. [41–43] have developed a projector and camera based method to maintain the required safety distance between the human and the moving robot (according to 'Speed and separation monitoring' in ISO TS 15066). In their method the robot working area is projected on the table with LED-DLP projector and the violations of the projected safety line is monitored with 2D industrial cameras at about 50Hz. In their latest paper [43] they demonstrated the method in an industrial workcell with a shared screwing task. The workspace is divided in two areas: a robot-area and a shared working area (for human and robot). The robot area is surrounded by fences from three sides and one side is monitored with the projector/camera system. When the robot enters to the shared area, the projected safety line moves in front of it. If a human hand intrudes to the robot area through the projected safety line, the robot stops. Requirements of ISO TS 15066 are taken into account in the worksite design.

Table 1 summarizes the reviewed vision based methods and provides some of their main features. In the table, the Bdiwi et al. [4] taxonomy of safety functions introduced in section 2, is used to evaluate which field of safety systems the authors have contributed.

4. Challenges of vision based safety systems

Based on all reviewed and analysed research the following challenges were found considering vision based safety systems. Occlusions in the robot workcell when there are multiple people or large objects may lead to situations where a human is not detected at a crucial moment. The experiments done by several authors have shown that the risk of occlusion can be decreased by using multiple sensors or sensor fusion. In general, 2D vision cameras are sufficient for object detection and identification, however, these are sensitive to light and dust in industrial environments. Other sensor modalities can be used to assist vision based methods by sensor fusion (e.g. sensitive skin on the robot). In the majority of the work collision avoidance has focused on the collision of the toolpoint and the human or an object in the workspace. Other robot joints have not been investigated for collisions. Especially for large and not inherently safe systems this is identified as a gap. Collision avoidance and motion planning considering real-time perception and reasoning has not been investigated and discussed in enough detail. More specifically, this implies latencies between control systems and delays in motion due to heavy robots with large inertia.

Finally, the introduction of new objects in a controlled man-

Table 1. Summary of the reviewed methods (Safety function: Related safety function according Bdiwi et al. [4] taxonomy; Robot zone state: dynamic = coupled with robot motion, static = limited predefined zone; Separation distance: dynamic = depends on robot speed, static = constant regardless of the robot speed; App: Demonstrated with real (industrial) application; NP: not provided).

Method	*Ref*	*Sensor type*	*Safety function [4]*	*Robot zone state*	*Separation distance*	*App*	*Other*
Safety EYE	Michalis et al 2015 [26]	3D camera	Safety-rated monitored stop	Static	Static	✓	Commercial, certified vision-based safety system
Projector and safety system	Vogel et al. 2017, 2013, 2011 [41–43], Leso et al [21]	2D camera	Safety-rated monitored stop	Dynamic	Dynamic	✓	LED-DLP projector, safety fences
Depth space distance calculation	Flacco et al. 2017, 2014, 2012 [11–13]	Multiple RGBD	Robot speed control (distance between robot and human)	Dynamic	Dynamic/static		Trajectory generation algorithm
Collision avoidance in an augmented environment	Mohammed et al. 2017 [27], Schmidt et al. 2014 [35,36], Wang et al. 2013 [44]	RGBD	Safety rated monitored stop, robot position control, robot speed controll (distance between robot and human)	Dynamic	Dynamic/static		3D model of robot
Level 3 HRI [4]	Bdiwi et al. 2017 [4]	RGBD and stereo cam	All	Dynamic/static	Dynamic/static	✓	Force/torque sensor
Kinetostatic safety field	Polverini et al. 2017, 2014 [30,31]	RGBD	Robot position control, robot speed control (distance between robot and human)	Dynamic	Dynamic		
Hand safety in assmbly phase	Cherubini et al. 2016 [7]	2D camera	Near field vision system: hand function	Static	Static	✓	trajectory optimization, admittance control, force/torque sensor
Human and robot replication in physics-based simulation	Morato et al. 2014[28]	Multiple RGBD	Robot position control, robot speed control (distance between robot and human), Near field vision system: upper body function	Dynamic	Dynamic/static		
Dynamic speed and separation monitoring	Vicentini et al. [40]	TOF	Robot position control, robot speed control (distance between robot and human)	Dynamic	Dynamic		SafeNet for unsafe devices
Reactive avoidance of moving obstacles	Saveriano and Lee [33,34]	RGBD	Robot position control	Dynamic	NP		
Earlly prediction of human motion in close proximity HRC	Mainprice and Berenson 2013 [22]	RGBD	Robot position control, near field vision system: upper body function, hand function	Dynamic	Dynamic/static		Swept volume of future motion of human
Integrated control for pHRI	De Luca and Flacco 2012 [9]	RGBD	Robot position control, robot speed controll (distance between the robot and human), near field vision system: upper body function, hand function	Dynamic	Dynamic/static		Residual-based method for collision detection
Sensor fusion for human safety	Rybski et al. 2012 [32]	Multiple TOFs and RGBDs	Robot position control, robot speed control (distance between robot and human)	Dynamic	Dynamic		
Triple stereovision system and colour markers	Tan and Arai [38]	Multiple stereo camera	Near field vision system: upper body function, hand function	NP	NP		Colour markers on the clothes
Visual tracking and intention estimation	Bascetta et al. 2011 [2]	2D surveillance cameras	Robot position control, robot speed control (distance between robot and human)	NP	NP		

ner by allowing a human and a robot to interact with unprogrammed tasks is identified as a future perspective. Intuitive and smooth interaction between a human and a robot can increase safety, reduce work load and allow for more efficiency in manufacturing environments.

5. Conclusions and future directions

This paper introduced a literature review of human-robot interaction and/or collaboration cases. The special focus was on vision based safety and alarming systems, although most of the reviewed cases relied on several technologies besides vision. Based on this overview a brief discussion on the challenges of vision as safety system is given to conclude this work. The findings are summarised in a table for easy comparison and classification. It is notable that while the technical solutions can be found there exist very few actual collaboration scenarios. In most of the cases the tasks are done in sequence, and could very well be fully automated assembly tasks. The human operator is mainly monitoring the tasks and his/her presence in the tasks is not continuous. The manufacturing or assembly tasks were done in constructed and relatively static environments.

The technical solutions presented in this paper, however, indicate that the technological barriers have been lowered in recent years thus enhancing the possibility to move towards real industrial cases with smaller lot sizes and dynamically changing environments. This shift towards human-robot collaboration in manufacturing therefore calls for documented standards and specifications that take the current state-of-the-art as well as the future perspectives into account. While much effort is ongoing towards this, these can be assisted by regular reviews and surveys that detail, compare and challenge the current state.

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