Proceedings Paper:

Cogurcu, Y.E., Douthwaite, J.A. and Maddock, S. orcid.org/0000-0003-3179-0263 (2022) Augmented reality for safety zones in human-robot collaboration. In: Turner, M. and Vangorp, P., (eds.) Computer Graphics & Visual Computing (CGVC) 2022. Computer Graphics & Visual Computing (CGVC) 2022, 15-16 Sep 2022, Virtual conference. Eurographics Digital Library .

EG UK Computer Graphics & Visual Computing (2022)
M. Turner and P. Vangorp (Editors)

Augmented Reality for Safety Zones in Human-Robot Collaboration

Yunus Emre Cogurcu[1], James A Douthwaite[2], and Steve Maddock[1]

[1]Department of Computer Science, The University of Sheffield, UK
[2]Department of Automatic Control & Systems Engineering, The University of Sheffield, UK

Abstract

Worker productivity in manufacturing could be increased by reducing the distance between robots and humans in human-robot collaboration (HRC). However, physical cages generally limit this interaction. We use Augmented Reality (AR) to visualise virtual safety zones on a real robot arm, thereby replacing the physical cages and bringing humans and robots closer together. We demonstrate this with a collaborative pick and place application that makes use of a Universal Robots 10 (UR10) robot arm and a Microsoft HoloLens 2 for control and visualisation. This mimics a real task in an industrial robot cell. The virtual safety zone sizes are based on ISO standards for HRC. However, we are the first to also consider hardware and network latencies in the calculations of the virtual safety zone sizes.

CCS Concepts

• ***Computing methodologies*** → *Augmented Reality; Safety; Safe Human-Robot Collaboration;* • ***Hardware*** → *Microsoft HoloLens 2; Robotiq Gripper 2F-85; Universal Robots 10 (UR10);*

1. Introduction

In human-robot collaborative manufacturing, robots are typically caged [20518] for worker safety. This restricts human-robot collaboration [MKK*18, HPL*20, HAMA19]. The hypothesis is that removing the cages around robots will increase human-robot interaction possibilities, thus providing flexibility and efficiency at the same time [HPL*20, HCL*21]. However, this raises safety issues.

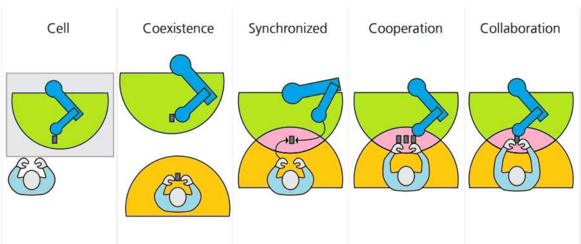

Figure 1: *Interaction types. The green area is the robot's workspace and the amber area is human's workspace. (The figure is based on one in [BBB*16].)*

Figure 1 shows different kinds of human-robot interaction [BBB*16]. We are interested in the three types where there is overlap between the human and robot spaces, so they can work in close proximity. In the synchronized type, the robot and human share a workspace, but the workflow means only one of them is in the workspace at a time. In the cooperation type, the robot and human work share the workspace but do not work on the same component simultaneously. In the collaboration type, the robot responds in real-time to the movement of the human as they work on the same component. The most common collaborative applications in use today are the coexistence and synchronized types [MKK*18, LAM*20].

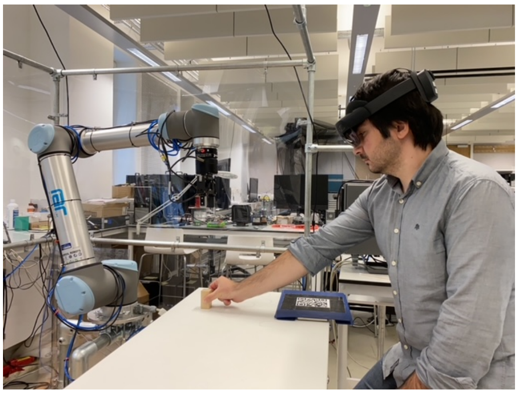

Figure 2: *Human-robot interaction with Universal Robots 10 (UR10) using Microsoft HoloLens 2.*

Previous studies of using augmented reality (AR) in human-robot collaboration (HRC) suggest that AR is a powerful tool for visualisation of safe areas [MMT*15, VPLS18]. Many different virtual barriers have been considered, such as 2D areas [LFK*21], safety curtains [HPL*20], user-configurable barriers (including around the user) [HCL*21], and geometric objects [CM21].

Our work builds on the idea of using virtual geometric objects to represent the safety zones around robot arms [CM21]. The virtual safety zone sizes are based on ISO standards but also take into account abstract hazards such as hardware and network latencies which have not been considered in other work. We demonstrate the use of the virtual safety zones in a collaborative pick-and-place application that mimics an industrial application. Microsoft's HoloLens 2 is used in the work as this is the most current and robust head mounted display (HMD) for use in the manufacturing industry. The Universal Robots 10 (UR10) robot arm was used because the UR10 robot arm is also used in real industrial applications.

The rest of the paper is organised as follows. Section 2 presents the related work. Section 3 describes the system which includes two servers and a HoloLens client. Section 4 describes how the AR safety zones are calculated. Section 5 presents the pick-and-place application and discusses the AR visualisation. Finally, Section 6 presents conclusions.

2. Related Work

AR can be utilised in industry to handle a wide variety of issues during the manufacturing of a product, such as planning, design, ergonomics assessment, operation guidance, training and safety [MZV17]. The objectives of using AR include reducing costs [MKK*18] and showing process steps to a user to explain complex information [DSHW18] or regulations [MIK*17, QKG*18]. Human-robot collaboration (HRC) is an increasing part of this [DLL21, NAWF21, EGGS20]. In terms of human safety and overall system productivity, AR is a powerful tool for the visualisation of robot operations and safe areas [MMT*15, VPLS18].

Hietanen et al [HPL*20] looked at two different AR display technologies (projection-based AR and Microsoft HoloLens 1) in a human-robot collaboration task involving a diesel engine assembly. Their system architecture was based on a Linux server to communicate with Robot Operating System (ROS) and HoloLens 1. They compared the use of a HoloLens 1 with AR projection. In both cases, depth sensor information was available for work space monitoring. Overall, they found that AR interaction reduced task completion time up to 21-24% and reduced robot idle time up to 57-64%. Their user survey suggested that the projector-mirror setup was easier and more comfortable to use than the HoloLens 1, which users felt to be heavy and uncomfortable to wear for long periods. Also, the small field of view of the HoloLens 1 was an issue. Lotsaris et al [LFK*21] also used ROS and HoloLens 1, making use of the RosBridge and Ros-Sharp open-source libraries for communication with the HoloLens 1. Their system shows robot sensor information and safety zones to a user. Again, there were comments about the HoloLens 1 being uncomfortable to wear for longer periods, making it unsuitable for full-scale use in a work environment. Another finding was that users wanted more descriptive AR user interfaces.

Hoang et al [HCL*21] proposed a virtual barrier system with an AR interface to ensure safe HRC. The system provides two types of virtual barriers. The first is a person barrier that surrounds and follows the user, and the second is a user-created virtual barrier for objects or areas. The proposed system compared performing a pick-and-place task that mimics an industrial manufacturing procedure with the Microsoft HoloLens 2 versus performing it using a standard 2D display interface. They concluded that the configurable virtual barrier system and AR improve the safety of HRC compared to a standard 2D display interface. Cogurcu and Maddock [CM21] experimented with user-configurable virtual geometric objects (cubes and cylinders) that wrapped around a virtual robot arm. These were either single shapes that dynamically changed size as the robot arm articulated or individual shapes that wrapped the pieces of the robot arm. Similar geometric objects are used as virtual safety zones in this paper, but these are attached to a real robot arm. In addition, virtual safety zone size calculations are based on a combination of ISO standards [fS16] and hardware and network latencies. Such latencies were not considered in any of the previous research.

3. The System

There are three main parts in the system (figure 3): a digital twin server, a Robot Operating System (ROS-Melodic) server and a HoloLens client. Both servers are physically connected to the same Local Area Network (LAN), with the HoloLens connected by WiFi. This decision was made to minimise the effects of latency whilst preserving the mobility of the human operator.

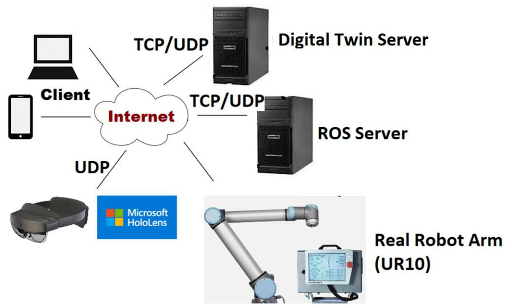

Figure 3: *The system architecture.*

The digital twin server is an active instance of the Digital Twin Framework (DTF) developed as part of the Confident Safety Integration for Collaborative Robotics (CSI:Cobot) project [CSI]. The DTF was developed in Unity3D as a modular framework for the development and testing of safety-critical digital twins [DLG*21]. The digital twin server hosts a virtual environment containing a 3D representation of the workspace, connections to the robot, other APIs (such as ROS) and network services. The HoloLens connects to the server to join the current workspace session and allow communication with the environment and the robot.

The digital twin server takes over all calculations of the client in the system. Thus, the client is a lightweight structure with only virtual models and a network component. Another important feature of this structure is that, for example, the kinematic calculations of the robot arm can be made via Matlab or ROS. In other words, without changing the client application, all the computational methods required in the digital twin server have been changed. So all the improvements made on the digital twin server are instantly viewable with HoloLens.

The Robotic Operating System (ROS) server was chosen to provide a connection layer that is common to both the DTF and the Universal Robots UR-10 robot arm. Communication between the ROS server and the DTF is persistent and bilateral, allowing information on the state of the physical system to be exchanged and feedback actions to be freely exchanged across multiple user sessions. For this paper, the server runs Ubuntu 18.04 with ROS-melodic. The Robotiq 2F-85 gripper is used as an end effector for the robot arm. This gripper is also controlled by ROS server. All the messages sent by the real robot arm are transferred over the ROS server to the digital twin server and then to the HoloLens 2.

The HoloLens operates as a network client to the digital twin server, providing access to the data-rich workspace in a format that is selective, functionally orientated and intuitive to the user. A Unity client application, also developed in Unity3D with Mixed Reality ToolKit (MRTK) version 2.7.3, runs on the HoloLens and communicates with the digital twin server via a UDP network interface.

The architectural design of the system addresses three main challenges with HRC applications and digital twins. These are broadly summarised as:

1. *Persistence* – HRI applications are necessarily momentary and intermittent as the operator engages with the robot. The DTF creates a persistent digital environment that the client interacts with without the dependence on the operator's involvement [BBD*18, DLG*21].
2. *Authority* – Authentication of users interacting with a digital twin is a vital step towards safe interaction with robotic systems. Our approach allows authority to be given to clients with known identities, and limit interaction when necessary.
3. *Performance* – The HoloLens 2 is one of the most powerful commercially available AR headsets. Despite this, its resources are limited as the complexity of the workspace becomes more advanced. With this server-client topology, all non-essential, non-user computation can be computed remotely, preserving local resources for specialist users and UI tasks.

A TCP/UDP protocol has been developed to enable this communication between the digital twin server and HoloLens. This communication is bilateral and the messages to be sent are transmitted in packets to the client or server with the appropriate protocol. In this way, it is ensured that new devices (e.g. tablets, phones or desktop) communicate with the digital twin server and the client application is platform-independent. In the current system, HoloLens 2 uses the UDP protocol.

One of the problems encountered when trying to place digital twins in the real world is how to position the digital twins. In our system this means aligning a virtual robot arm with the real robot arm. We use a QR code to facilitate this. The QR code is detected by the HoloLens 2 and the virtual robot arm's coordinate system is aligned with the real-world location of the QR code. This process is currently manual. After alignment, the same ROS commands issued to both the real robot arm and virtual robot arm keep them in sync meaning that any virtual safety zones stay aligned with the real robot arm. The virtual robot arm is made invisible.

4. Safety Zone Calculations

ISO/TS 15066:2016 [fS16] sets out the safety requirements for collaborative industrial robots and the work environment and also complements the requirements and guidance on the use of collaborative industrial robots defined in ISO 10218-1 and ISO 10218-2. As part of the CSI:Cobot project [LAM*20], we use Speed & Separation Monitoring (SSM) scenarios, combining the AR system with the SSM calculations, as will now be described.

4.1. Speed & Separation Monitoring

ISO/TS 15066 is concerned with clarifying four different types of cooperation scenarios: safety-rated Monitored Stop, Hand-Guiding, Speed and Separation Monitoring, and Power and Force Limiting. Since these different types of collaboration are already present in ISO 10218, the new standards will clarify specific points, especially regarding the maximum speed and maximum value of pressure and force allowed to achieve safe human-robot collaboration. For simultaneous tasks, SSM is preferred by industry [LAM*20, VPLS18].

In the speed and separation method, the robot and operator can be in the collaborative workspace simultaneously. The risk is reduced by constantly maintaining the Protective Separation Distance (PSD) between the operator and the robot. PSD can be calculated according to ISO/TS 15066. The relevant values to be calculated are (i) the intrusion distance that a part of the body can move toward the hazard zone before actuation of the safeguard (C) and (ii) position uncertainty for both the robot and operator (Zd + Zr). In addition to these values, the distance at which the robot can stop without causing an accident at time t0 is calculated with the following formula from ISO/TS 15066, taking into account the operator's position change (Sh), the robot's position change (Sr), and the robot's stopping distance (Ss):

$$S_p(t_0) = S_h + S_r + S_s + C + Z_d + Z_r$$

Hence, the minimum safety distance (PSD) is found by the sum of C + Zd + Zr. The constant C is set at 88 mm as defined by ISO 13855 [13810]. To calculate the maximum robot position uncertainty, the robot controller latency is calculated to be 8 ms. We know that the robot controller outputs position data every 4 ms, which we sample asynchronously to calculate this. In the worst case, if the data output occurs at t = 0 but we do not sample until (say) 3.9999ms have elapsed, we have a 4+3.9999ms delay on the robot position reporting a maximum of 8ms. The operator's speed (Vh) is calculated to be a worst-case maximum of 1600 mm/s by ISO 13855. Thus, multiplying robot reaction time or robot controller latency with the human speed gives Zr + Zd:

$$C = 88mm \text{ (defined by ISO 13855)}$$

$$Zr + Zd = 1600mm/s \text{ x } 0.08s = 128mm$$

The minimum safety distance (PSD) is thus $128mm + 88mm = 21.6cm$. This refers to the minimum safety zone from the tool centre point of the robot arm. In other words, it is the minimum distance that must be between the human and the robot.

4.1.1. Hardware Latency

The HoloLens 2 has latency when displaying 3D models, which can vary based on scene complexity. During the tests, it was observed that the delay of the HoloLens 2 varied between 14 and 50 milliseconds. In order to create the safest situation in the creation of the safety zone, the worst value, 50 milliseconds, was chosen.

Adding the latency of the HoloLens ($Z_{HoloLens}$) now gives us:

$$S_p(t_0) = S_h + S_r + S_s + C + Z_d + Z_r + Z_{HoloLens}$$

To calculate a safety margin for network latency or hardware latency, the latency value must take into account human speed:

$$Z_{SafetyMargin} = \text{Human Speed (mm/s) x Latency (s)}$$

$$Z_{HoloLens} = 1600mm/s \text{ x } 0.05s = 80 \text{ mm} = 8 \text{ cm}$$

Thus when using HoloLens 2 an extra 80 mm safety margin is added on top of the standard safety zone size.

4.1.2. Network Latency

Another important issue is network latency in our client-server architecture. In order to minimise the possible delay during the tests, the digital twin server, ROS server and robot arm use the same router. The delay between the digital twin server and the ROS server is calculated as a minimum of 7 and a maximum of 20 milliseconds. The delay between the ROS server and the robot arm is calculated as a minimum of 7 and a maximum of 20 milliseconds. The delays within the robot itself are negligible.

Network latency caused by HoloLens and the digital twin server is the most important value to consider. Although HoloLens and other servers are connected to the same router, HoloLens connects to the digital twin server via wireless. This is why the delay between HoloLens and the digital twin server is higher than other delays.

During the experiments, the lowest latency between HoloLens and the digital twin server was 7 milliseconds, while the highest value was 50 milliseconds. As mentioned above, the highest value between HoloLens and the digital twin server is taken as 50 milliseconds in order to provide the safest human-robot collaboration.

In order to ensure the maximum safe HRC, the worst-case values are selected. Each server has 20 milliseconds of network latency and the network latency between digital twin server and HoloLens is 50 milliseconds so the total network latency is 90 milliseconds. This gives an additional safety margin that must be included:

$$Z_{NetworkLatency} = 1600mm/s \text{ x } 0.09s = 140 \text{ mm} = 14.4 \text{ cm}$$

5. A Pick-and-Place Application

To test the system, a pick-and-place application was implemented. This involves moving wooden blocks (a child's toy) from area A on a tabletop to area C on a separate table via area B in front of the user (see figure 4). The robot arm moves a block from area A to area B and the user then moves the block from area B to area C. Figure 4 shows initial test positions for areas A, B and C.

The user wears a Microsoft HoloLens 2 throughout the task and sees the virtual safety zones overlaid on the real robot arm. Safety zone configurations and robot arm movement can be controlled from the AR interface (see figure 5).

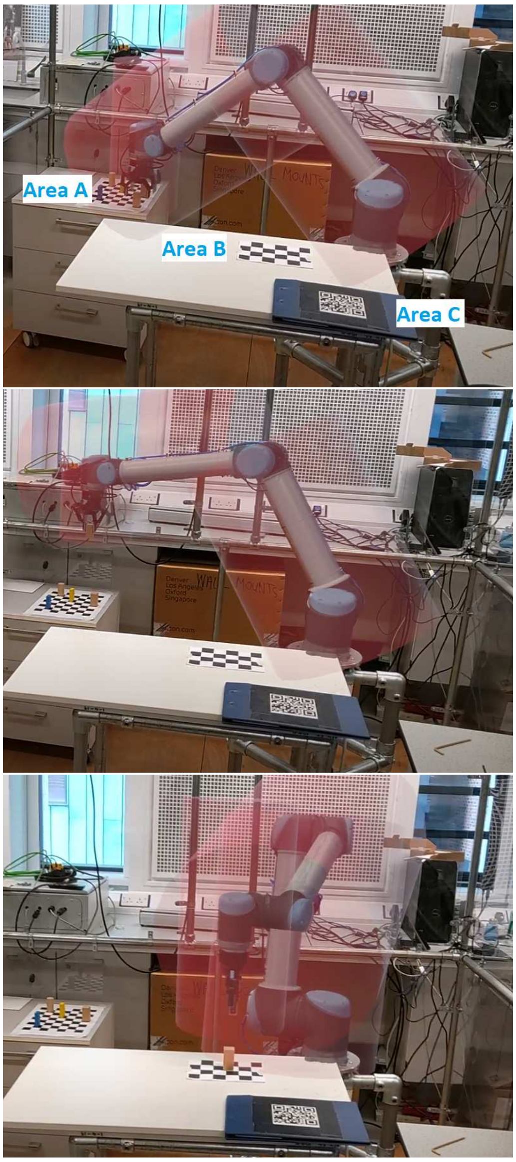

Figure 4: *The robot arm picks up a wooden block from area A and moves it to area B, the middle of the table.*

Four different safety zones based on the calculations in section 4 are available:

- a single, dynamically-sized, virtual cage (cuboid) around the whole robot arm with size based on the robot arm's pose and the ISO 15066 standard (figure 6);
- a single, dynamically-sized, virtual cage (cuboid) around the whole robot arm with size based on the robot arm's pose and the ISO 15066 standard, with an extra distance layer for hardware and network latencies (figure 7);

Figure 5: *Panel type user interface for HoloLens 2. The safety zones can be configured using the UI.*

- a sectional virtual cage (a collection of cylinders around the main parts of the robot arm) with size based on the ISO 15066 standard (figure 8);
- a sectional virtual cage (collection of cylinders around the main parts of the robot arm) with size based on the ISO 15066 standard and an extra distance layer for hardware and network latencies (figure 9).

The cuboid safety zones change size as the robot arm moves, whilst respecting IS0 15066, thus occupying less volume that a fixed physical cage. As the robot arm moves to area A, the dynamically-changing cuboid stretches from the robot base to area A, and the user can use area B without violating the safety zone. If the user's hand strays into a safety zone, the robot arm immediately stops moving. A pop-up menu item allows the user to start the robot arm's movement again.

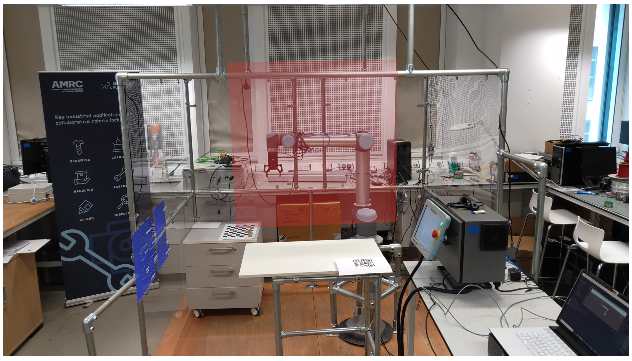

Figure 6: *Single cuboid safety zone.*

The aim of the sectional cylinder safety zones is to produce less dead space than the single cuboids and potentially closer cooperation between human and robot, since the human is less likely to trigger the robot arm to stop. Our hypothesis is that the extra large safety zones (including hardware and network latencies) will, however, make users feel safer when collaborating with the robot arm. This has yet to be tested though. Note that areas A, B and C in figure 9 have changed slightly from the initial test in figure 4, with a box used for area C.

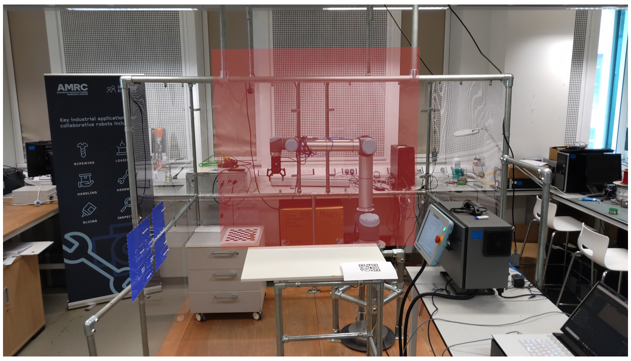

Figure 7: *Single cuboid safety zone with hardware and network latency layer.*

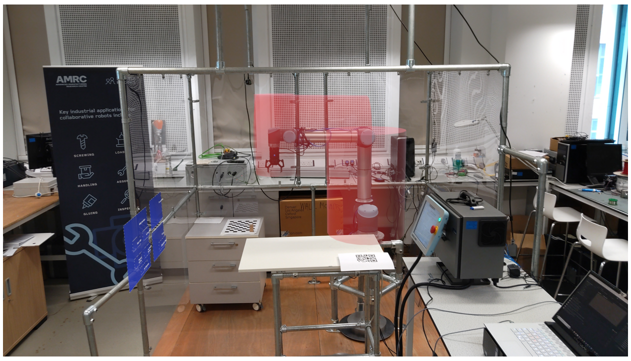

Figure 8: *Sectional cylinder safety zone.*

Figure 5 showed part of the user interface, which floats in the virtual 3D space around the robot arm. These and other menus can be moved and docked and a range of options are available to alter the visualisation aspects of the AR safety zones. Again, a user study is required to determine how usable this menu system is.

Figure 9: *Sectional cylinder safety zone with hardware and network latency layer. The viewpoint is changed in this figure to show the position of the robot arm with respect to the table. Areas A, B and C are also labelled.*

6. Conclusions

We have presented a system that uses AR to display safety zones for a real robot arm in a collaborative pick-and-place application. Two different safety zone shapes, cube and cylindrical, have been visualised around the real robot arm. The size of these takes into account hardware and network latencies and is user configurable. The next step is a user evaluation of the use of AR safety zones and which type and size makes a user feel safer.

References

[13810] 13855 I.: Safety of machinery — positioning of safeguards with respect to the approach speeds of parts of the human body, 2010. 3

[20518] 2050 F.: Real benefits of virtual simulation(https://www.amrc.co.uk/news/real-benefits-of-virtual-simulation), Oct 2018. 1

[BBB*16] Bauer W., Bender M., Braun M., Rally P., Scholtz O.: Lightweight robots in manual assembly—best to start simply. *Frauenhofer-Institut für Arbeitswirtschaft und Organisation IAO, Stuttgart* (2016). 1

[BBD*18] Bolton A., Butler L., Dabson I., Enzer M., Evans M., Fenemore T., Harradence F.: *The Gemini Principles*. Tech. rep., Centre for Digital Built Britain, Cambridge, 2018. 3

[CM21] Cogurcu Y., Maddock S.: An augmented reality system for safe human-robot collaboration. In *4th UK-RAS Conference for PhD Students & Early-Career Researchers on" Robotics at Home"* (2021), UK-RAS Network. 1, 2

[CSI] Confident safety integration for collaborative robots. https://www.sheffield.ac.uk/sheffieldrobotics/about/csi-cobot. Accessed: 2022-06-20. 2

[DLG*21] Douthwaite J., Lesage B., Gleirscher M., Calinescu R., Aitken J. M., Alexander R., Law J.: A modular digital twinning framework for safety assurance of collaborative robotics. *Frontiers in Robotics and AI 8* (2021). URL: https://www.frontiersin.org/article/10.3389/frobt.2021.758099, doi:10.3389/frobt.2021.758099. 2, 3

[DLL21] Dianatfar M., Latokartano J., Lanz M.: Review on existing vr/ar solutions in human–robot collaboration. *Procedia CIRP 97* (2021), 407–411. 2

[DSHW18] Danielsson O., Syberfeldt A., Holm M., Wang L.: Operators perspective on augmented reality as a support tool in engine assembly. *Procedia CIRP 72* (2018), 45–50. 2

[EGGS20] Evjemo L. D., Gjerstad T., Grøtli E. I., Sziebig G.: Trends in smart manufacturing: Role of humans and industrial robots in smart factories. *Current Robotics Reports 1*, 2 (2020), 35–41. 2

[fS16] for Standardization I. O.: Robots and robotic devices collaborative robots. *ISO/TS 15066:2016* (2016). 2, 3

[HAMA19] Hentout A., Aouache M., Maoudj A., Akli I.: Human–robot interaction in industrial collaborative robotics: a literature review of the decade 2008–2017. *Advanced Robotics 33*, 15-16 (2019), 764–799. 1

[HCL*21] Hoang K. C., Chan W. P., Lay S., Cosgun A., Croft E.: Virtual barriers in augmented reality for safe and effective human-robot cooperation in manufacturing. *arXiv preprint arXiv:2104.05211* (2021). 1, 2

[HPL*20] Hietanen A., Pieters R., Lanz M., Latokartano J., Kämäräinen J.-K.: Ar-based interaction for human-robot collaborative manufacturing. *Robotics and Computer-Integrated Manufacturing 63* (2020), 101891. 1, 2

[LAM*20] Law P. I. D. J., Aitken C.-I. D. J. M., Mihaylova P. L., Calinescu D. R., Alexander D. R., Clark P. J.: Confident safety integration for cobots (csi: Cobot), lloyds registry foundation, 2019-2020. 1, 3

[LFK*21] Lotsaris K., Fousekis N., Koukas S., Aivaliotis S., Kousi N., Michalos G., Makris S.: Augmented reality (ar) based framework for supporting human workers in flexible manufacturing. *Procedia CIRP 96* (2021), 301–306. 1, 2

[MIK*17] Maurtua I., Ibarguren A., Kildal J., Susperregi L., Sierra B.: Human–robot collaboration in industrial applications: Safety, interaction and trust. *International Journal of Advanced Robotic Systems 14*, 4 (2017), 1729881417716010. 2

[MKK*18] Michalos G., Kousi N., Karagiannis P., Gkournelos C., Dimoulas K., Koukas S., Mparis K., Papavasileiou A., Makris S.: Seamless human robot collaborative assembly–an automotive case study. *Mechatronics 55* (2018), 194–211. 1, 2

[MMT*15] Michalos G., Makris S., Tsarouchi P., Guasch T., Kontovrakis D., Chryssolouris G.: Design considerations for safe human-robot collaborative workplaces. *Procedia CIrP 37* (2015), 248–253. 1, 2

[MZV17] Mourtzis D., Zogopoulos V., Vlachou E.: Augmented reality application to support remote maintenance as a service in the robotics industry. *Procedia CIRP 63* (2017), 46–51. 2

[NAWF21] Nicora M. L., Ambrosetti R., Wiens G. J., Fassi I.: Human–robot collaboration in smart manufacturing: Robot reactive behavior intelligence. *Journal of Manufacturing Science and Engineering 143*, 3 (2021), 031009. 2

[QKG*18] Quandt M., Knoke B., Gorldt C., Freitag M., Thoben K.-D.: General requirements for industrial augmented reality applications. *Procedia CIRP 72*, 1 (2018), 1130–1135. 2

[VPLS18] Villani V., Pini F., Leali F., Secchi C.: Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications. *Mechatronics 55* (2018), 248–266. 1, 2, 3