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Toward safer Human-Robot collaboration in MR environment

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Abstract

This paper presents a Mixed Reality (MR) approach to extend the Safe Move tool from ABB Robot Studio (RS) to view and intuitively edit the safety configuration, allowing the import of existing configurations and the export of modified ones to RS for certification by the expert. The added virtual sensor can detect the user's position allowing collision detection and avoidance. The robot's motion is not only adjusted to the safety zone in which the robot is but also to its relative position to the operator by monitoring in real-time positions of the operator's hands as well as head and triggering appropriate action in the robot.

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1. Introduction

Toward a sustainable and human-centric production system within the concept of Industry 5.0 [1], the cyber-physical systems with human-in-the-loop, according to [2], aim to become safety-engineered systems using adaptive control, advanced communication, and context-sensitive technologies to interface machines, software, and humans in the physical and virtual worlds.

Targeting this concept, the paper presents a Mixed Reality (MR) approach to extend the Visual SafeMove Configurator tool from ABB Robot Studio® (RS) to view and edit the safety configuration, allowing the import of existing configurations and the export of modified ones to RS for certification by the expert. However, this tool allows to define and use the safety features on the MR environment without connecting expressly to RS, granting it to be repurposed for other software and robots. Moreover, implemented virtual sensors can detect the user position allowing collision detection and avoidance by adjusting for robot motion not only due to the safety zone in which the robot is but also to its relative position to the operator.

The main contributions of our research are: (1) visualization and intuitive modification of safety configuration for industrial cobots; (2) smooth change between programming on a laptop and in MR; (3) use of wearable MR device as additional safety monitoring device; (4) use of simulation to detect potential collisions beforehand. The rest of the paper is organized as follows. Section 2 gives an overview of the relevant literature. Section 3 presents the proposed system. Section 4 highlights the implementation details. Finally, Section 5 summarizes the conclusions and outlines our future work.

2. Literature

In the last decade, robots have experienced an evolution in favor of human safety thanks to embedded torque monitoring that can detect collisions between the robot's body and the human. These kinds of improved robots are called collaborative robots or cobots. However, collaborative robots are still incapable of detecting the position of the user without the use of external means.

Initially, Augmented Reality (AR) and MR were employed as support tools for robot programming, as Honig et al. [3] pointed out easy debugging and a reduced gap between simulation and implementation as the main benefits of using MR in robotics. For example, Ostanin et al. [4] presented a MR system for easily assigning tasks to the robot manipulator without the need for programming skills. In early works, the safety aspects were side effects of increased situational awareness. [5, 6] presented an AR tool for supporting operators in a hybrid, human-robot collaborative industrial workspace. The system provides instructions and improves the operator’s acceptance of the hybrid environment and safety.

Several studies demonstrate the importance of safety in robotic cells. For example, [7] discussed the safety assurance of cobots in the aspects of critical functional requirements, standardizations, and safety mechanisms. In particular, they mentioned that, in designing and building a cobot, safety assurance factors must be incorporated into robotic structures, motion controls, mechanical systems, virtual commissioning, and human-robot interfaces.

Regarding human-robot interfaces, AR and MR can be used to visualize safety zones for increased situational awareness. [8] presented an AR application to facilitate the operators' work in a flexible environment with collaborative mobile robots. The system includes safety zones visualization to support the operator. Another safety visualization is developed in [9], where the HoloLens 2 (HL2) were used to augment the safety information obtained from the monitoring system based on two Kinect Azure RGB-D cameras. More examples are found in [10], where the developed AR solution provides the operator virtual interfaces to program mobile robots, and safety awareness by superimposing the active safety zones around the robots.

As mentioned before, the visualization of safety zones in AR has been explored by several studies. The purpose of using AR is to improve the user’s comprehension of the robot’s workspace in comparison to visualization on a computer. In particular, RS provides a tool called Visual SafeMove [11] that can be used to both visualize and edit safety zones around ABB robots. However, the advantages of setting safety zones in the Visual SafeMove tool are restricted to a 2D environment, where it is necessary to have a 3D model of the workspace or to know beforehand the dimensions of the safe zone.

3. Overview

This work proposes a novel approach to integrate MR for safety configuration and validation as well as an additional layer of safety in Human-robot interactions (HRI). The Safety Configurator originated as an MR extension of the Visual SafeMove [ABB Robotics 2022] tool in Robot Studio®. The Visual SafeMove tool allows the user to establish safety zones around the robot and to encapsulate the upper arm and the tool, creating a safety configuration file that can be acknowledged and certified by an engineer.

In the same way, the MR safety configurator in the proposed approach can create different types of sensors in the MR station, from scratch or by importing them from Robot Studio and elaborating a final export file that is synchronized with

Robot Studio again. Using the safety configurator, it is possible to create virtual sensors in the HL2 which are not only used to program the safety zones, but are also capable of detecting in real-time the user presence in robot proximity and triggering a halt in either the virtual or real robot. This way, programming and editing of the safety zones, as well as user detection, can be done inside the same environment in MR in an easy way.

Moreover, the safety configurator was created with the purpose of providing a quick and smooth change between programming on a laptop and in MR. This is possible because the safety configurator is synchronized with Robot Studio in real-time. Any configuration file from Robot Studio can be imported instantaneously into the safety configuration in the MR environment, and vice versa. This means that it is possible to start configuring a safety zone in the laptop, continue the work in the HL2, and finish by certifying safety in Robot Studio (Fig. 1).

The implemented tool allows performing of several activities related to safety that are discussed in the following subsections. However, the virtual sensors in the HL2 cannot be directly used as a certified safety configuration for a real robot cell as the certification has to be first approved in the Robot Studio.

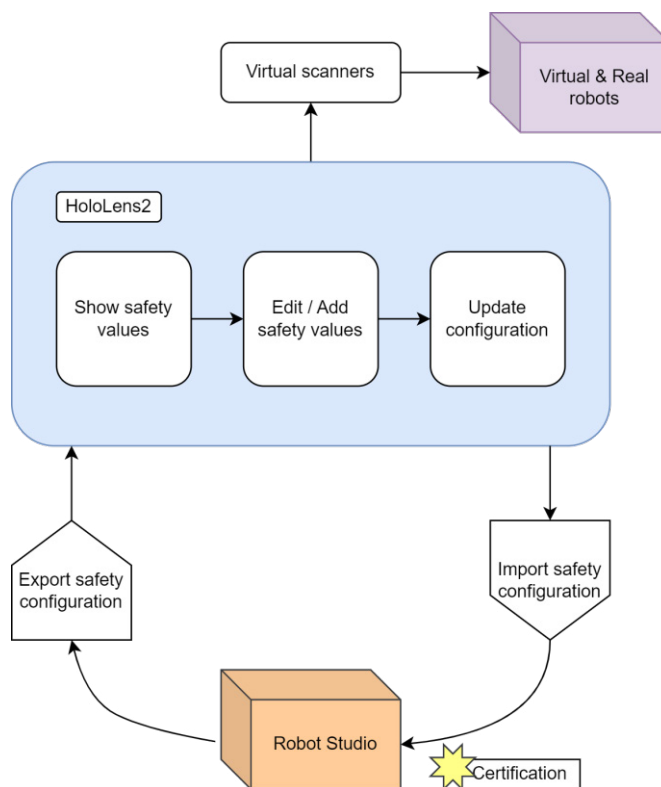


Fig.1. Flowchart of the Safety Configuration.

3.1. Implemented functionalities

The safety configurator has been programmed to support the edition and customization of safety zones in the MR environment in the HL2.

Inside the application, it is possible to import any type of safety configuration from Robot Studio and visualize it in the MR environment, but also create a new one from the HL2. In

addition, it can be complemented by adding more sensors to the station according to their purpose, having box sensors for smaller objects or grid sensors for bigger volumes.

As for the robot itself, the MR platform allows the encapsulation of the upper arm and tool, either for the real or the virtual robot. The enclosure is conducted with virtual spheres and/or capsules, conforming to the safety criteria.

Regarding areas, dynamic grids can be created or imported from RS, and personalized by adding or removing grid points.

Concerning the path, there is a possibility to automatically encapsulate it, updating itself with the path when this one is modified. As the path is a key feature in robot programming, this sensor includes a fading material when the user is close to ensure the visibility of the targets.

All these sensors can be resized, replaced, and rotated as well as hidden to avoid visual cluster while keeping their functionality.

The usage of the safety configurator is beyond just the editing of safety zones since it is also intended to act as a detector of human presence to avoid dangerous situations. Therefore, it also supports the customization of the action triggered on the robots when a human is close, from a stop to a slow down, and the future state, either continue performing the path or completely stop. This is by virtue of tracking the body of the wearer, who is informed as soon as there is a safety violation.

The bidirectional communication allows to easily export the station configuration to the virtual controller connected in the same format ABB uses so it can be reopened in RS. This process, as the importing feature, is done automatically without the need for external tools, and the file created on the MR environment will be converted and transferred to the connected device immediately without interruptions.

Moreover, a collision prediction for welding pieces feature can be activated, so that the virtual robot can detect collisions in advance and stop if necessary by running the virtual robot a few seconds ahead of the real one.

3.2. User interface in the HoloLens 2

Every feature of the safety configurator in the HL2 application is accessible through a virtual green menu as shown in Fig. 2. It contains all buttons related to functionalities explained in the previous section.

- **Import:** button to show the safety configuration uploaded in Robot Studio. Each time a Robot Studio configuration is imported, the encapsulations, sensors, and grids will be added to the station in MR.
- **Export:** to automatically send the actual safety configuration values in the station to the computer where Robot Studio is. The corresponding safety configuration xml file will be created in a desktop folder that can be opened in Robot Studio at any moment.
- **Hide/Remove:** to activate a blue menu to hide the view or remove existing sensors in the station.
- **Cube:** to create a default box sensor in front of the robot. The difference with grids is that box sensors are intended to be small/encapsulate the path.



Fig. 2. Main menu of the safety configurator.

- **Edit:** to resize, replace and rotate sensors. In particular, grid sensors are resized with little white boxes in the grid's vertices, as shown in Fig. 3.

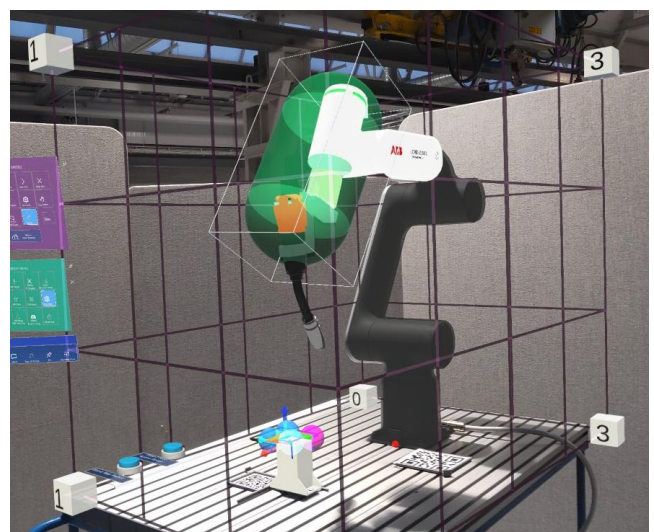


Fig. 3. Safety Configurator in edit mode.

- **Encapsulate Path:** this button encapsulates automatically the robot's path in the station with a box sensor. If a target is grabbed, the encapsulation will resize itself to contain the target. Regarding the material of the virtual encapsulation, its transparency is higher in order to not disturb the view of the station, while the edges are opaquer to make the limits of the box clear. In addition, this material fades when the user gets close to the targets or the welding piece (Fig. 4).

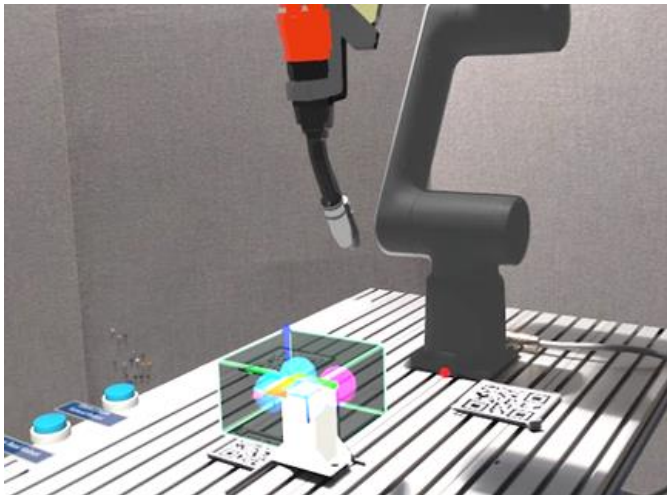


Fig.4. Encapsulation of the targets in a welding piece.

- **Grid action toggle:** to choose which action will be triggered when a collision between the user and a grid occurs (stop or slow down).
- **Sphere, capsule:** to create a default sphere/capsule in the location specified by the toggles "In Tool" and "In Arm".
- **Encapsulate robot:** to load a recommended safety configuration for the encapsulation of the robot.
- **Detect collisions:** the virtual robot moves 4 seconds ahead of the real robot to detect future collisions with the welding piece.

In addition to the main menu, two blue menus appear when pressing the "Edit" button. More information about these menus and the whole application can be found in video [12].

3.3. User Interface in Robot Studio

A Robot Studio Add-In was developed to exchange the safety configuration data between the HL2 and Robot Studio. Through the Add-In, it is possible to:

- Connect Robot Studio to the HL2 through a server. This is done by activating the server and selecting the IP.
- Select the safety file that will be sent to the HL2.
- Show a QR code that will contain the IP address of the server so that the HoloLens can dynamically update that information.

4. Implementation

In this study, ABB CRB 15000 GoFa cobot was used. The GoFa has integrated torque sensors in each of its six joints to

bring GoFa to an immediate stop if any contact with a human worker is sensed. It is controlled by an OmniCore controller with RobotWare 7.5.2 with RobotStudio 2021.4 used for offline programming and the certification of safety configuration. The HL2 application was developed with the use of Visual Studio 2022, .Net 5.0 Unity 2021, and MRTK packages.

4.1. Implementation in Unity

The presented application has been developed in C# using Unity and the Mixed Reality Toolkit (MRTK). Logic underneath the safety configurator is based on a finite-state machine where each state is a safety case. Changes between safety cases are triggered when the user enters or exits a safety zone area, either grids or other types of sensors. Five main safety cases have been specified:

- **Case 0:** the user is outside the working area, and the robot is moving at full speed.
- **Case 1:** there has been a collision with a virtual sensor. The virtual and the real robot are stopped and the user is warned through an MR pop-up.
- **Case 2:** after a collision state, the user has exited the dangerous zone and the task can be resumed.
- **Case 3:** a user has been detected inside a zone where the robot should slow down.
- **Case 4:** after a slow-down state, the user has exited the dangerous zone and the task can be resumed at full speed.

The current safety case is shared in real-time with the virtual and real controller to stop, slow down or resume the task in the robot immediately after the user has touched one of the virtual sensors. An example of how to place those virtual sensors in a welding cell is depicted in Figure 5.

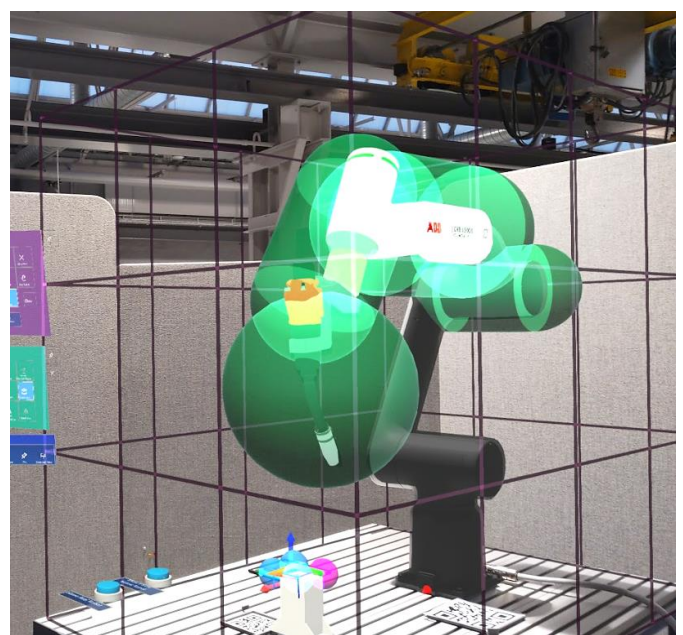


Fig. 5. Robotic cell with a virtual and a real robot, a grid sensor and three virtual sensors encapsulating the robot (green).

Table 1. Types of virtual sensors in the safety configurator.

Sensor	MAX no	Parent	Material	Robot action	Collider	TAG
Grid	Inf.	Robot base	Grid	Stop/slow down	Mesh	GridSensor
Box	Inf.	Robot base	Trans.	Stop	Box	VirtualSensor
Box Path	1	Welding piece	Trans. + fade	Stop	Box	VirtualSensor
Sphere	2/4*	Joint 4/ tool	Trans.	Stop	Sphere	VirtualSensor
Capsule	2/4*	Joint 4 / tool	Trans.	Stop	Mesh + spheres	VirtualSensor
Head	1	Head	Invisible	-	Capsule	UserSensor
Hand	2	Hands	Invisible	-	Spheres	UserSensor

(*) max sensors in arm = 2, max sensor in tool=4

Regarding the implementation of virtual sensors, seven different types of sensors (see Table 1.) have been implemented to increase the flexibility of the safety configurator:

- **Box sensors:** sensors in the shape of a box that are attached to the station. Their size is customizable
- **Box path:** this sensor contains the encapsulation of the path and its material fades when the user gets closer.
- **Grid:** prismatic sensors with a customizable number of sides. The color of a grid sensor changes every time a new grid is created to ease the differentiation.
- **Spheres and capsules:** these sensors are attached to the robot's arm or tool. In particular, capsule sensors have been developed so that the top and bottom spheres do not experience deformation when the capsule is resized, as in Robot Studio.
- **Head and hand sensors:** invisible sensors are attached to the user's hands and head to determine when a virtual sensor has been touched. This is possible thanks to the HL2 capability of tracking hands and head.

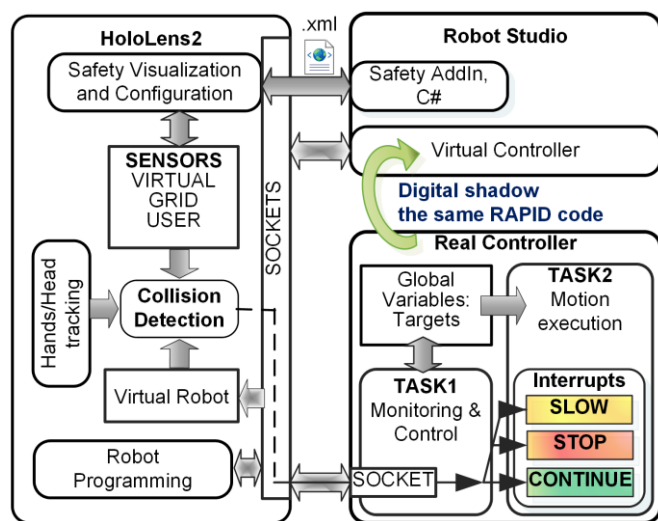


Fig. 6. Overview of the system components and communications between components i.e. HoloLens 2, Real Controller, Virtual Controller, and Robot Studio Add-In.

4.2. Communication

Communication between the HL2, the Virtual Controller (VC), and the Real Controller (RC) is achieved with three TCP/IP servers, one of them located in the Virtual Controller and the other one in the Real Controller; and an extra server is in the Robot Studio Add-In for exchange of safety data. When the servers are initialized, they keep waiting for an incoming connection from the client. In this case, the HL2 (client) will trigger the communication between the server every time it is needed (Fig. 6). In VC and RC the servers are implemented with the use of a multitasking option to allow socket communication in parallel to the execution of motion task.

Digital shadow for collision prediction

The virtual robot in the MR environment follows in real time the movements of the robot in Robot Studio (VC) and the real robot (RC). This behavior was achieved by the exchange of target, speed, and joint data through the TCP/IP servers previously explained. Information about the position of targets is generated in the HL2 and sent to VC, which answers with joint data when the task starts. Information about joints is used to update the robot in the HL2.

This principle defines the base for collision prediction since the virtual robot is started 4 seconds ahead of the real robot. If the virtual robot detects a collision in the MR environment, a command is sent to RC to stop the real robot instantaneously. Moreover, based on the selected scenario the robot could also slow down or return to a normal operation mode.

4.3. Robot Studio Add-In

The Add-In integrated with the proposed application was built on a base of Tommy Svensson's previous work, which was adapted to receive/send safety data from/to the HoloLens. In Robot Studio, safety data is defined as an xml file that contains the number and type of sensors, their dimensions, positions, etc. This data is sent from the Add-In to the HL2 when the MR button "Import" is pressed. Once in the HoloLens, the information inside the xml file is used to create the virtual sensors. The inverse process occurs when the user presses the MR button "Export", where virtual sensors in the HoloLens are translated to an xml file which is received by the Add-In in Robot Studio. In fact, the Add-In is the reason for the seamless interaction between the MR world and the computer when working with the safety configurator.

5. Conclusions and future work

MR technology has shown great potential in creating virtual sensors that increase safety in robotic cells. The development and application of MR-based virtual sensors have resulted in positive outcomes since they were capable of detecting humans in dangerous situations while reducing the need for physical sensors. Despite the evolution of cobots towards safer collaboration with humans, these robots are still incapable of detecting the position of the user. Therefore, using a wearable MR device as an additional layer of safety has the potential to provide a solution to this issue.

Moreover, the proposed safety configurator allows visualization and intuitive modification of safety configuration for industrial cobots. It is fully customizable and provides a seamless change between the computer and the HL2. Customization is also achieved by the addition of different layers of safety depending on the robot's action when the user touches a virtual sensor. For this reason, MR technology provides flexibility and scalability in the deployment of virtual sensors, making it suitable for various industrial applications.

Furthermore, the utilization of simulation through the MR environment has demonstrated successful outcomes in detecting potential collisions and subsequently halting the real robot. Such a strategy can prove to be advantageous in preventing collisions with real assets.

Our future work will focus on more seamless integration with Robot Studio to allow certification of safety configuration via an interface in HL2. Moreover, the presented approach could be extended to be able to handle cells with multiple robots.

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