DESIGNING A DYNAMICALLY CONFIGURABLE DIGITAL TWIN FOR HUMAN-ROBOT COLLABORATION TASKS

A Case of Working Environment Configuration for the Robotic Lab

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Abstract. This paper presents a novel Digital Twin scenario for enhancing Human-Robot Collaboration (HRC) in the context of Industry 4.0. Traditional HRC environments, characterised by their repetitive and standardised tasks, are limited in adapting to dynamic and custom requirements. We propose a dynamically configurable Digital Twin (DCDT) system, enabling dynamic configuration of virtual HRC workspaces for creative design and prototyping, addressing the limitations of conventional HRC environments confined to repetitive tasks. By integrating AR, the system allows human operators to intuitively interact with robots, planning and simulating robotic trajectories with interactive holographic visualisations. We cooperate with The Design Modelling and Fabrication (DMaF) Lab at The University of Sydney and propose a workflow based on the DCDT system to assist students complete basic robot co-creative drawing programming under routine teaching scenarios. This research underscores the importance of AR in bridging the gap between physical and virtual workspaces, facilitating a flexible and efficient HRC setup. Future work will focus on refining the technology, addressing scalability, and exploring its adaptability to various creative and prototyping domains.

Keywords. Augmented Reality (AR), Digital Twin, Human-robot Collaboration (HRC), Human-robot Interaction (HRI), Robotic Fabrication, Industry 4.0.

1. Introduction

In the industrial workplace, human agents have a highly flexible and adaptable role, and industrial robots have been regarded as synonymous with high precision and efficiency (Wang et al., 2021). Conventional fabrication and assembly processes are

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labour-intensive and the interaction with large robotic arms is not friendly to human operators due to various reasons such as safety issues (Acioli et al., 2021). With the arrival of Industry 4.0 and the applied integration of cyber-physical systems for sensors and network control systems, industrial robots are endowed with the capability to perceive the external environment and to communicate information based on cloud computing (Czifra & Molnár, 2020). This intelligent transformation has generated new opportunities for human-robot collaboration (HRC) working environments with working scenario that combines the flexibility of a human with the high efficiency and high pay-load characteristics of a robot, allowing the production line to quickly respond to the changes in the supply and demand relationship of specific commodities in the Industry 4.0 era (Wang et al., 2021). To integrate an HRC workspace in the production line, the typical method is to construct a digital twin for the corresponding scene (Malik & Brem, 2021). For example, the user can manipulate the virtual agent to affect the behaviour of the physical object. A virtual environment is set up with the necessary information needed for human operators to complete a task with the robot(s), including physical objects such as workpieces and fixtures, hardware connections to robots and other devices such as sensors (Holubek et al., 2018). Typically, designing a digital twin is divided into four steps:(1) formulation of task aims; (2) selection of resources;(3) digital design of workspace and (4) system verification. This development method of the digital twin is for working environments with consistent processes using standard physical objects (parts) (Yin et al., 2023). However, when irregular objects or customised services are introduced, this poses a challenge to the digital twin because the virtual environment needs to be adapted to custom objects and tasks.

Hence, this paper aims to develop a new digital twin scenario that allows the human agent to dynamically configure the layout of a virtual HRC workspace by adapting to the change in the physical environment and its objects. We use an AR-based user interface application through HoloLens 2 to assist the human operator to connect and simulate the robot(s) in cyberspace. The user can adjust the virtual workspace and plan robotic trajectories through the AR interface developed by Unity3D. The simulated content will be synchronously displayed on the AR headset in the form of a series of Holograms. When users are satisfied with the simulation, they can follow the prompt of the AR interface sending the configuration information back to Rhino/Grasshopper. The robotic programming plugins such as KUKA|prc and Robots for Grasshopper is responsible for converting the simulation data of robotic motion into the kinematic control signal and passing it to the physical robotic arm, enabling the robot to execute the HRC task set by the user in the digital twin. In order to demonstrate how this proposed system can be applied in the practical scenario, in this paper, we cooperate with The Design Modelling and Fabrication (DMaF) Lab at The University of Sydney University, assisting a Lab Robotics Prototyping Officer (Lynn Masuda - second author) to design dynamic configuration system for existing devices and workspaces. The main users of the lab are undergraduates and postgraduate students who have limited experience in using and programming the robotic arm. Therefore, an interactable digital twin environment is required during the teaching process making students can quickly understand the working environment and learn robot programming. Hence, we classify lab devices and working environments into four categories: “Robots”, “End Effectors (Tools)”, “Working Space” and “Workpieces” and redesign corresponding 3D model libraries for this digital twin scenario. The lab user can create a specific robotic working scene from these digital libraries and plan the motion path for the selected robot through the AR interface. At the end of this paper, we discuss the advantages and disadvantages of this new digital twin scenario according to the case of the robotic lab and present future improvements.

1.1. AR AND INDUSTRIAL ROBOTICS IN FABRICATION

The design of the interaction experience plays a significant role in boosting the next industrial revolution (Leng et al., 2022). Typically, a robot is limited by its physical morphology, such as its kinetic structure - gesture, movement, and physical transformation or the visual output - fixed and small display, and sound and lights (Baraka et al., 2016), which is difficult to represent additional information beyond intrinsic physical constraints (Walker et al., 2018). The feature of AR to expand and superimpose virtual information of relatively constrained real objects enables it to be a strong contender to address these challenges. Additionally demonstrating virtual and physical reality content in the same vision field can alleviate the problem of breaking the consistency of interactive experience when the human's field of view switches back and forth between the external screen and robots.

According to research by Song et al. (2021) AR-based user interface for robotic control and AR-based programming by demonstration (PbD) method are the two main application scenarios in fabrication. The UI system can display functions of robot status and information applied for simplifying operations, improving safety and maintenance. PbD is used to allow untrained users to develop robotic tasks in a more intuitive way. However, most current AR usage scenarios are in the early stage which makes invisible information visible. With the popularity of robotic arms in digital fabrication, how to use AR to allow designers and architects without programming experience to interact with robots in an efficient and reasonable way has become a pressing challenge.

1.2. DIGITIAL TWIN

With the digital transformation demands brought about by Industry 4.0, the need for Digital Twin is discovered and promoted from the aerospace sector to encompass broader applications (e.g. developing, creating, training and maintenance) in industries such as manufacturing and digital fabrication (Singh et al., 2021). The current core concept of the Digital Twin is a system that can couple the physical and virtual agent, integrating the strengths of both physical entities and virtual representation to advance the entire system (Jones et al., 2020). In this process, the effectiveness of implementing two key technical indicators - "physical-to-virtual connection" and "virtual-to-physical connection" - affects the operation and the performance of the Digital Twin system (Jones et al., 2020). Therefore, in the physical environment, the common solution is to maintain the use of the latest sensors enhancing the accuracy of environmental detection or apply faster network connection speeds feeding back to the virtual twin efficiently (Cheng et al., 2018). In the virtual environment, this is achieved through reflecting more information in terminal, increasing accuracy of process control, and enhancing production management to complete the higher precision simulation, thereby synchronising with the physical twin. These methods can help enterprises improve productivity and efficiency when dealing with traditional production lines and standardised construction requirements in manufacturing. However, when facing tasks where objectives need to change frequently, such as HRC creative projects or processing non-standardised workpieces in digital fabrication, the current Digital twin processes, which focus solely on precision, are unable to fully function. We need a type of Digital Twin that can dynamically configure according to user requirements to meet changing and complex application scenarios.

2. Methodology and Technology

This research proposes a new Digital Twin system named the dynamically configurable Digital Twin (DCDT) system to assist general users with limited robotic programming and using experience to collaborate with the industrial robot in a creative and random scenario. In this section, we will elaborate on the process of development and operating mechanism of the DCDT system. In the next section, we cooperate with DMaF Lab to extract the co-creative teaching scenario that occurs most frequently in the daily operation activities of the Lab. This scenario is aimed at teaching robotic basic knowledge to undergraduates and postgraduates who lack experience in robotic programming experience. At the end of the teaching activities, students are asked to independently complete the programming task for robot drawing. We provide insights into designing a new workflow based on the DCDT system for this special scenario.

2.1. PROCESS OF DEVELOPMENT AND OPERATING MECHANISM

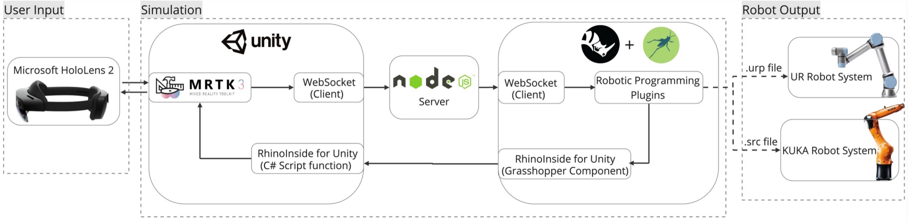

Figure 1. the systematic diagram of the dynamically configurable Digital Twin (DCDT) system

As shown in Figure 1, the entire DCDT system consists of three parts. Part one - User Input - utilises the Microsoft HoloLens 2 AR headset as the method of interaction detection and input between the user and the virtual space. Compared with other AR devices, HoloLens 2 supports more accurate hand tracking and recognition of more gestures such as touching, grasping, and moving without using the controller. Thus, for the DCDT system applied in creative scenarios, these features can expand more interaction possibilities for interactions. In order to cooperate with the development of HoloLens 2, the latest Microsoft AR development solution MRTK3 has been adopted. It includes a package of performance optimisation features for the AR headsets the most important of which is the support of Unity3D-based AR programs as well as the third-generation AR user interface (UI) design elements and guidance. The DCDT system follows this solution and uses Unity3D as the development platform for the AR application. Namely, when HoloLens 2 detects the user's interactive input from the first part, the program designed by MRTK3 in Unity3D is responsible for receiving, storing and processing the input signal, to provide a data basis for subsequent system operation.

The role of Unity3D is to demonstrate digital twin simulation content in the AR headset to the user, allowing them to configure the virtual twin via AR UI in combination with the corresponding physical twin. Once the interactive information of user input from HoloLens 2 is determined to be valid, Unity3D, as a client, will package it as a JSON file and send it to the server via WebSocket communication protocol. The server, built by Node.js, will receive the user input data and pass it to the Rhino/Grasshopper. We use the Bengesht plugin to construe the WebSocket in Grasshopper. As another client, when Grasshopper receives packaged JSON user input information from the server, the JSON function of the ShapeDiver plugin is used to unpack the file. Different input information controls different functions of the robotic programming plugin (Robots and KUKA|prc), such as the selection of robot type or the installation of the end effector. With the open source "Rhinoinside for Unity" program, a series of robot simulation content selected by user input information will be synchronised to Unity3D in the form of 3D modelling. HoloLens 2 can display this 3D simulation through the MRTK3 to the user, completing the configurable simulation loop of the DCDT system.

As the last part of the DCDT system, robot control is responsible for exporting user-configured and designed robot control information to the physical robotic arm. When the user is satisfied with the series of robot configurations and motion planning they have completed following the guidance of the AR UI, this selected combination will be saved by Grasshopper and converted into a control program file for the physical robot through the robotic programming plugin. UR Series robots correspond to ".urp" files, while KUKA series robots correspond to ".src" files, with running the control program file to build the virtual-to-physical link for the DCDT system.

3. Project Tests and Outcomes

3.1. WORKFLOW OF THE DMAF LAB TEACHING SCENARIO

As shown in Figure 2, through analysing the content of the robotic basic knowledge teaching process in DMaF Lab, the workflow can be divided into four main steps corresponding to four functions: (1) Robot System; (2) End Effectors; (3) WorkSpace (Base/Table); (4) Workpiece. The first function is defined as a display and selection for all robotic arms. In the previous teaching scenario, students are first introduced to basic knowledge about robots, which includes identifying different robotic systems, types, and naming conventions, among other content. However, the traditional mode uses a 2D screen combined with slides and Rhino/Grasshopper to present 3D robotic content, which fails to create an intuitive and immersive experience. Especially during the Rhino/Grasshopper demonstrations, frequent replacement of robot components will cause confusion for students. Therefore, in the first step of the workflow, we use the DCDT system to archive two robotic systems - the KUKA series robots and the UR series robots - contained in the Lab, so that students can choose and display the true-to-scale 3D robot content in HoloLens, with the help of a carefully designed AR UI. Through evaluation, five models of KUKA robots are listed and modelled, including four types of industrial robots " KR6 R900 ", " KR10 R1100 ", " KR60 - 3 " and " KR120 R2900 " and one type of smart collaborative robot " LBR iiwa 14 R820". For the UR robots, "UR5e" and "UR10e" are chosen to be included in the Robot System.

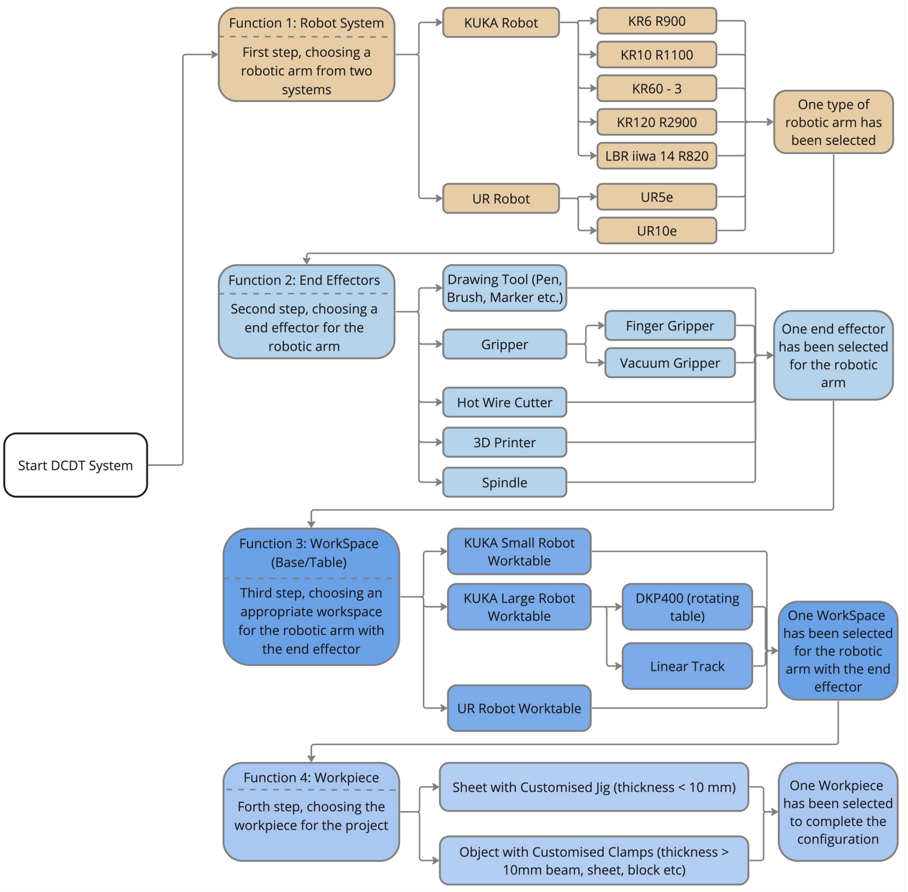

Figure 2. the workflow of the DCDT system for the DMaF Lab teaching scenario

After participants complete a study of robot taxonomy, they can select one of the robots that they would like to collaborate with via AR UI and bring it to the second step of the workflow, which involves the installation, adaption and use of the robotic end effectors. For robots to contribute to a specific task, they must be equipped with the corresponding end effectors to implement and achieve the task aim. For example, as one of the most used end effectors, the gripper can help robots complete take-and-place tasks. So, by sorting out the various end effectors in the DMaF Lab, we identify six types of end effectors that are commonly used in teaching activities and are compatible with various robot models, provided for students to learn and use. They share a common feature - the ability to program robots in relatively simple and limited steps. In addition to the two variations (finger gripper and vacuum gripper) of the gripper, Function 2 also provides the selection of four other tools: "Drawing Tool (Pen, Brush, Marker etc.)", "Hot Wire Cutter", "3D Printer" and "Spindle". One thing that needs to be explained is that the drawing tool, whether a pen, brush or marker is securely fixed inside a 3D-printed holder bolted to the end of the robotic arm. This holder has been designed at DMaF Lab with interchangeable components, allowing for 3D printing of parts to adapt to various drawing tools with varying diameter thicknesses. Students can match the robot selected from Function 1 with the appropriate tool based on the robotic task aim and each selected tool will be "installed" on the virtual robot, visually displayed in the AR space through the DCDT system.

After students have determined a specific combination, the workflow will move to the third stage - WorkSpace (Base/Table). We propose a unified mobile workspace, integrating the working base and robot into a single unit. This configuration features a steel-framed table on wheels, with the robotic arm securely fixed at one corner and the robot controller housed beneath. The table's threaded top allows users to securely affix workpieces and custom jigs using M10 bolts. This adaptable setup provides users with the flexibility to reach specific positions on the table, in the event of positional errors or collisions during simulation. We design three types of mobile workspaces to accommodate different kinds of robots and their sizes. They are "KUKA Small Robot Worktable", "KUKA Large Robot Worktable" and "UR Robot Worktable". Depending on the type of robot selected previously, one specific workspace can be selected and displayed simultaneously in HoloLens 2.

Although various robot tools such as grippers or 3D printers were mentioned in the previous Function 2, they are all designed for the early stage to help students understand robots and their components. The purpose of this case is to teach student how to use robotic arm. To quickly achieve this goal, the final activity of this case is designed to have students complete programming of the robotic drawing task. So, for the last function, we only retain the drawing canvas and grabbable workpiece as content for student to choose and use. The drawing canvas will be a single A3 sheet of paper (297 mm x 420 mm) that will be taped onto a customised jig made at DMaF Lab (480 x 580). The jig is a 6mm sheet of plywood that is bolted onto the robot table using M10 bolts. Once the final workpiece is selected, the overall construction of the Digital Twin for the DMaF Lab teaching scenario is completed. Specific details about the design of the AR UI and the final control process for the physical twin of the robotic arm will be elaborated in the next section.

3.2. THE DEMONSTRATION OF THE DCDT SYSTEM FOR THE CASE

According to the workflow, a series of AR UI based on four functions is designed aiming to help students handle collaborative tasks with industrial robots. We mainly used the Air Tap gesture supported in HoloLens 2 to configure related functions of the robot and used the same gesture to creatively plan the robotic drawing trajectory. The default hand ray in HoloLens 2 is used for enhancing the perception of hand position tracking. Therefore, based on these conditions, we fully developed the DCDT system and used the built-in video recording function in HoloLens 2 to film the demonstration.

The storyboard in Figure 3 is responsible for demonstrating the details of the AR UI and specific operation processes. It should be noted that, in order to better demonstrate the interaction details, the first 8 frames of the storyboard feature the AR UI viewport made by Figma to showcase the scene layout with content and UI. The 9th frame of the storyboard uses a clip from the actual robot execution video to demonstrate the outcome of the collaborative drawing task. When the student puts on the HoloLens 2 and enters the DCDT system, they will see the welcome interface shown in Storyboard 1. This interface is a brief introduction to the DCDT system and will guide the student to click the "Start" button to enter subsequent functions. At this time, if the students raise their hands, they will see the hand rays extending from the hands (one ray for each hand) and these rays will move with the movement of the hand. At the end of the hand ray is a donut-shaped cursor, intuitively indicating where the ray intersects with the interactive object such as a button. The students can control the hand ray to move to the "Start" button by moving their hands and pinch the thumb and index finger to complete the Air Tap gesture (commit interaction), entering the next interface. The UI contents of Storyboard 2 and 3 correspond to the first function - Robot System - of the DCDT system mentioned in section 3.1. In this demonstration, the KUKA KR6 R900 is finally selected. Turning on attention back to the UI of Storyboard 4, it includes all the end effectors mentioned above. In this frame, a clip shows the installation of a drawing tool in the physical KR6. Therefore, based on the change in physical conditions, the drawing tool is determined to be the end effector used by the KR6 digital twin. Similarly, after the selection of the end effector, in Storyboard 5, the virtual robot is equipped with a drawing tool to provide feedback to the students that the configuration has been successful. The next step is to choose the workspace (base/table) for KR6. In this frame, the students can clearly see the small KUKA table used by the physical KR6 through the HoloLens 2, so they can directly select the corresponding digital representation by using the AR UI, and this choice will also be synchronously displayed in Storyboard 7. A sheet with a customised jig on the robot table is affixed by M10 bolts and according to this situation, the students can simply choose the corresponding option to complete the virtual configuration.

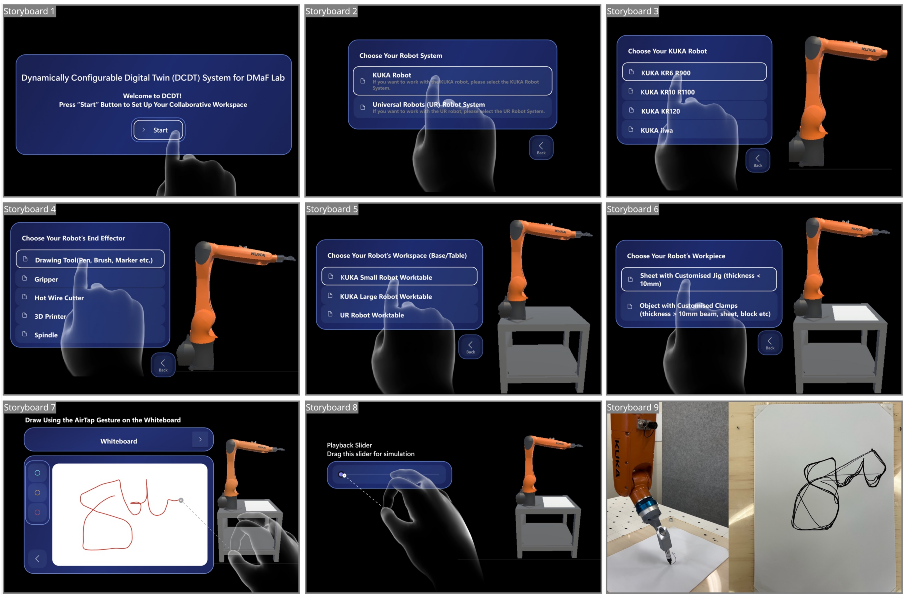

Figure 3. the storyboard of using the DCDT system to program the robotic arm drawing task

Given that the task aim of this case is to develop the robotic drawing programming, an interactive drawing whiteboard is proposed after completing the configuration of the four main functions mentioned in the previous workflow. Students can approach the whiteboard and use their fingers to draw on it. The drawing content is transferred from Unity3D to Rhino/Grasshopper for analysing and processing by using the same WebSocket communication protocol mentioned in section 2. Through the robotic programming plugin, the drawing strokes are compiled into robotic movement path. After students finish drawings, they can submit their work and use the playback slider mentioned in Storyboard 8 to simulate and observe the robotic path. If there are no errors and the students are satisfied with the drawing programming, they can choose to export the robotic control path as an executed ".src" for the physical KUKA KR6. Finally, in Storyboard 9, the physical KUKA KR6 runs the file, drawing the pattern (designed by the students on the virtual whiteboard) on the sheet affixed on the small KUKA worktable.

4. Discussion

The current Digital Twin focuses on using advanced technical means and standardised processes to enhance the accuracy of connection between the physical to virtual space. However, it has not adequately addressed the growing demand of digital configuration for dynamic user needs in the Industry 4.0 framework. In this paper, we propose a system named DCDT, which offers a novel AR-based solution for the current development of creative prototyping and design applications in the HRC field. The system operates as described in Figure 1, using HoloLens 2 as a medium, allowing users with limited robotic programming experience to set the configuration of robotic virtual twins and plan robotic action paths through a well-designed AR UI and 3D virtual presentation scenes. We cooperate with DMaF Lab to develop a workflow based on the operational mechanism of the DCDT system. By analysing the details of the Lab's routine activities (teaching), four main functions were identified to compose the minimal system of the DCDT for completing robotic programming. A storyboard, created from frames extracted from HoloLens 2 recorded videos, provides a detailed demonstration of the AR UI and explanation of the process of controlling a robot to complete a drawing task. This process validates the contribution of the DCDT system to a creative HRC project: (1) teaching basic robotic programming knowledge support for users with limited robot programming background; (2) the operational mechanism of the proposed DCDT System successfully displays accurate robotic 3D digital twin from the Rhino/Grasshopper robotic programming plugin in HoloLens 2, allowing bidirectional information exchange through the AR UI; (3) the workflow based on real application scenarios efficiently integrates with the DCDT system to provide rapid HRC application design and development.

There are two things worth noting about the current version of the DCDT system. First, the content and interaction details of the current AR UI will require subsequent iterations with target user testing. Second, the content of the workflow was developed based on the DMaF Lab's teaching activity - robot drawing programming, hence its adaptability to other creative and prototyping domains is unknown. Future versions will need to continue to test universality and improve adaptability in different scenarios.

5. Conclusion

This paper has discussed an innovative digital twin scenario tailored for Human-Robot Collaboration (HRC) within the realm of Industry 4.0, with a primary focus on prototyping and creative design. Addressing the constraints of traditional HRC environments with confined to repetitive and standardised tasks, the proposed system, leverages Augmented Reality (AR) through HoloLens 2 and so allows for the dynamic configuration of virtual HRC workspaces.

An integration of AR fosters real-time, flexible interaction between human operators and robots, which is required in creative and dynamic environments. Through an intuitive AR interface, this system facilitates the planning and simulation of robotic trajectories, complemented by interactive holographic visualisations provided by the digital twin. The case study indicates efficacy in educating students with limited robotics experience. However, technological dependencies, potential AR-related challenges, and scalability concerns warrant attention for future refinement. This paper serves as a catalyst for ongoing discussions, emphasising the need for continued exploration, improvement, and integration of such technologies to drive innovation in Industry 4.0 and beyond.

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