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Initial Framework Design of a Digital Twin Mixed-Reality-Application on Human-Robot Bi-Directional Collaboration for Forming Double Curvature Plate

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Abstract

This paper endeavors to explore and identify commonalities among recent definitions of Digital Twin (DT) technology. additionally, it introduces a framework for a digital twin of Human-Robot Collaboration (HRC) with a particular focus on English wheel manufacturing as its foundational context. To achieve this, two 3D simulators, namely Grasshopper and Rhino, were employed to faithfully replicate the English wheel process digitally. Subsequently, an optimization of these simulators' performance paved the way for a comprehensive visualization of the English wheel using the Microsoft HoloLens. This visualization integrates digital and physical interactions, resulting in a mixed reality environment. The ultimate goal of this research is to enable a bi-directional collaboration within the digital representation of the English wheel, bridging the gap between the virtual and physical realms.

Keywords: Digital Twin; Human-Robot Collaboration; Mixed Reality; Industry 4.0; Digital Manufacturing

1. Introduction

Evolving technology drives changes in industry. Currently, within manufacturing, Industry 4.0 concepts have begun to become more widespread including Digital Twins (DT), Big Data Analysis (BDA) and Internet of Things (IOT) [1]. The goals of such technologies include the development of open, smart manufacturing platforms, transformation of machines into self-ware, self-learning systems that can interact with sensors and other machines, and the use of data collected from sensors to aid production and organizational decision making [1].

In the physical realm, Industry 4.0 has ushered in the increased use of robotics – which function as power and flexible fabrication tools. In the last two decades, increased affordability of industrial robots along with the growing maturity of computational design software has also contributed to the adoption of these machines. The size of the global market for industrial robots continues to increase with almost 2.1 million new robots installed between 2018 and 2021 [1]. This, however, only captures the trends in the physical realm within Industry 4.0.

DTs aim to create cyber-physical amalgamations. The term was first presented by Michael Grieves in a 2003 presentation on product lifecycle management (PLM) [2]. Micheal Grieves gave DT as a concept that contains three main parts: a physical product in real space, a virtual product in virtual space, and the connections of data and information that ties the virtual and physical product together [2]. The first prime example of DTs implementation was observed in 1970 in space robotics from NASA, when the phrase had not been invented yet [3]. The term NASA used at the time was "living model" [3]. It was used for the historic Apollo 13 mission, which incorporated innovative robotic technologies used for vital functionalities such as docking [3]. The DT employed back then was a multi-simulator cyber-physical system that focused on physical infrastructure, as opposed to the real-time integration of physical and virtual replicas observed today [3]. The mission also marked DT's first triumph in space robotics, as the technology was successfully deployed to safely return crew from impending danger caused by an oxygen tank explosion aboard the craft [3]. On the industrial side, use of DTs has appeared in several large enterprises, such as General Electric, Siemens, PTC, Dassault Systems, and Tesla, which use DTs to increase their product performance, manufacturing flexibility, and competitiveness [2]. Recently, van Beek et al. wrote a perspective piece on how the DT concept can enable the integration of system design decisions and operational decisions during each state of a system's life cycle [4].

At a top-level, the creation of a DT is done by recreating the physical objects in a high-fidelity virtual environment. In this virtual environment, several simulations can be created based on real-world physical objects and interactions. From these simulations, real-world decisions can be made thus creating a bi-directional mapping [1,2,4]. Due to the growing volume of literature, DT has been used erratically to describe various connections between physical and digital components, often muddling a concise definition [3]. The communication infrastructure between the physical and digital components, which is unilateral or not considered, differs between concepts like Digital Shadow (DS) and Digital Model (DM) [3]. This is because a DS only allows communication of the physical world into the digital world, and a DM has no communication between the physical world and the digital world. Thus, the composition of what a DT is a particularly important distinction. The purposed composition of what a DT is comes from these six crucial components: physical representation, virtual representation, virtual simulation, and bidirectional communication, online predictive control, and model update.

After knowing the physical system that the DT will be built upon, the next part is building the high-fidelity virtual world. There are several ways to build and visualize the virtual world - one way is to build the virtual world in a program such as Unity3D or Unreal3D and display it on a monitor. More immersive visual experiences exist such as extended reality. Extended reality is split into three distinct categories: Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). These three categories commonly come from Milgram's Reality-Virtuality Continuum. The Reality-Virtuality (RV) continuum, as initially proposed by Milgram and Kishino, is shown in Fig. 1. They consider any environment that consists of a blending of real and virtual objects to be a MR. MR environment where the real world is augmented with virtual content are called AR, while those where most of the content is virtual but there is some awareness or inclusion of real-world objects are called augmented virtuality (AV) [5]. There have been many projects involving all three main categories of VR. The applications range from direct control commands for robots to predictive maintenance and learning factories. The trend of more mobile devices, such as cellular devices, in factories also results in interesting approaches for showing real-time instructions in AR [6]. The DT in these systems is typically manipulated manually. Approaches leveraging Artificial Intelligence (AI) in DTs to automate and optimize have begun to be implemented. Muller et al. use DT and AI models to acquire and automatically label data for synthesis, accelerating dataset training [7].

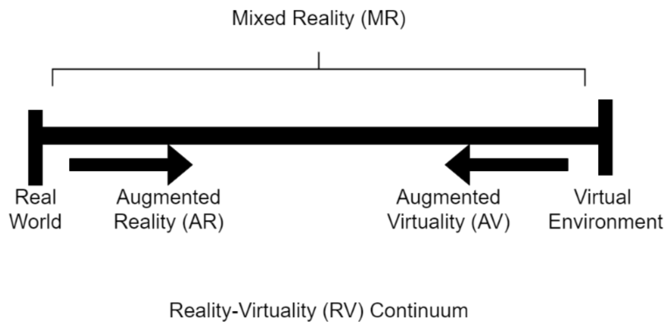

Fig. 1. Milgram Reality-Virtuality Continuum

Thus, we arrive at our research objective, to create a bidirectional communication DT that uses mixed reality for interactions. In section 2, mixed reality within DTs is explored and defined. Section 3 describes the proposed bidirectional system for the DT. Section 4 goes over how remote collaboration can happen with DTs. Section 5 discusses robotic forming using the English wheel, which will be used as a test case for DT model building. Section 6 and Section 7 review the proposed method for creating the DT and human-computer interaction (HCI). Lastly, Section 8 is the discussion and conclusion of the paper, along with future directions.

2. Definition of MR in DT

In virtualization, there are three main categories of how to represent the virtual world. These three main categories are Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). The main difference between these categories is the involvement of the physical world. VR has no physical world, only a virtual world and AR has no interaction with the physical world, while MR can interact and have input from the physical world.

A more in-depth definition of MR is that it fuses the real world and virtual space to create a new visual environment. In the new visualization environment, physical and digital objects co-exist and interact in real-time. The goal of MR is to integrate virtual and reality seamlessly to form a new virtual world that includes characteristics of a real environment for virtual objects. The MR system can not only realize the two-way interaction between the users and the virtual space but also realize the two-way interaction between users and the physical space. Finally, due to the MR system, physical space could also realize two-way interaction. For this two-way interaction, the MR system needs information from virtual space, real-time information from physical space, and sensory & feedback information from the user. In addition, in the process of two-way interaction, the MR system will play a role that process and converting key information. What is more, this information is distributed and superimposed to build the MR scenes we need [5].

For other research and literature, MR is in a design phase where the researchers are designing the framework for how the MR application will work. In this literature as an example, the researchers are creating a MR scenario for a DT in the context of a system of systems. The researchers found that with this hybrid MR scenario, it is possible to place the virtual smart scale on the real autonomous construction site and thus integrate it flexibly into the physically running workflow. This provides the opportunity to flexibly test the use of the smart scale at different positions. The construction site vehicle approaches the virtual scale before and after loads. Since the measurement itself cannot be carried out by the still virtually integrated smart scale, a fictitious measured value of the weight must be entered by the user at this point, which is later taken over by the actual measurement of the real smart scale. The weight is then processed by information technology and transmitted to the associated construction vehicle and the higher-level System of Systems (SoS) system. Thus, the entire workflow of the smart scale is functionally and procedurally carried out once at this position. For optimization, the process can be repeated at any number of positions after a short adjustment based on the knowledge gained [17]. This is why this research is choosing a MR application of DTs due to this bi-directional communication from the physical world and the virtual world.

The combination of the use of the bi-directional communication of MR applications and the use of Artificial Intelligence (AI) is enabled in many different areas. In the manufacturing field, these applications can range from training to maintenance to logistics. For example, MR and AI integration enables real-time object recognition and interaction for IoT machines and devices in Industry 4.0. MR and AI integration is essential for achieving real-time automatic object detection and human-machine interaction. Therefore, MR and AI cannot be substituted by other approaches. These technologies can be applied to logistics warehouses and require the integration of IoT technologies. This not only increases the efficiency of depositing and retrieving specific objects but also improves the overall management of items in the warehouse [7]. In other studies, MR has utilized deep learning (DL) algorithms to provide user-centric task assistance through object detection and instance segmentation. A study proposed an integrated MR system for safety-aware human-robot collaboration (HRC) using DL and DT generation. The proposed approach can accurately measure the minimum safe distance in real-time and provide MR-based task assistance to the human operator The real-time safety distance calculation can be conducted by finding the distance between the human skeleton and robot link with offset radii instead of calculating the distance between 3D point clouds, widely used in previous studies. Thus, the approach in the study can verify the real-time applicability and accurate safety distance calculation for safety-aware human-robot interaction [8].

This leads into what the next section will go over which is collaborative robots and the cyber-physical bidirectional system. As an overview, collaborative robots are robots that are used in combination with a human operator to complete a task together. This is the human-robot interaction discussed at the end of the last paragraph, the study that provided a system that was for the safety needed for human-robot interaction. However, this research is going to go over a framework for a MR application that uses collaborative robots for bending sheet metal.

3. Collaborative Robots, Mapping, and Cyber-Physical Bidirectional System

3.1. Collaborative Robots

Collaboration with robots is commonplace in the manufacturing field. This collaboration is an umbrella for anything a robot and a human make together. An example of this would be the manufacturing of cars or even computer chips. However, due to the increase in technology, the manufacturing industry is looking to improve this collaboration from the machines and humans doing the task separately to having the humans and robots work together on the same task. This means collaboration needs to evolve and become more flexible, and responsive, and in some cases having all the machines on the same network all communicating with each other. This is where researchers are designing applications to handle and meet the needs of the manufacturing industry called Human-Machine Interaction (HM) systems.

HMI systems at the center are systems to handle the communication, cooperation, and interaction between humans and machines. The benefits of HRC in industrial applications are restricted by various requirements for safety production. In an HRC process, humans and robots need to cooperate closely and intensively, and the most basic and critical issue is ensuring the safety of collaborators [9]. For this reason, the International Safety Standards (ISO) have issued ISO 10218–1 and ISO 10218–2 to determine specific applications and standards for joint operations [9]. Safety control strategies of HRC need to be considered in two stages, before and after the collision. Before the collision, visual image processing technologies and intelligent algorithms are used to predict the potential collision in advance, to give alternative control robot solutions. After the collision, the collected contact information (e.g., data from tactile sensors, changes in the internal current of the robot, etc.) determines if a collision has occurred and whether necessary measures should be adopted to reduce the damage caused by the robot to people [9].

For this research, we are using the HRC system to bend a sheet of metal on an English Wheel. The way the collaboration works is by using sensors and the position of the robot's gripper, then we can know how much force from the English wheel to apply. The force of the English Wheel is controlled by the human. After the robot is finished bending the metal the human operator then inspects the sheet of metal to make sure the curvature is correct. A more detailed explanation will be discussed in the later section.

3.2. Mapping

Mapping the real world into the virtual world is critical to the success of this research. The reason the mapping is critical is because if the measurements are wrong for any part of the system the simulation cannot be accurate. This creates the DT to be wrong and the research to be invalidated.

For the DT not to be invalidated in the future due to the wrong mapping of the physical world, a series of measurements were taken of the machines and the materials used. The measurements of machines were taken using a variety of instruments. For example, a ruler was used to make sure the measurements of the wheels were the same as the listed measurements from the manufacturer. After assuring the measurement machines and metal plates were correct, a one-to-one recreation was made in the virtual world. Next, we needed to match the movement of the collaborative robot and the one used in the real world. Luckily, the Grasshopper3D program that was used accepted the commands used by the robot. This meant that the collaborative robot in the virtual world would move just like the collaborative robot in the physical world.

3.3. Cyber-Physical System

In the space of DTs there is often a misconception that a DT is a Cyber-Physical System. The reason that this is a misconception and wrong is that a DT is an interconnected bidirectional virtual model that represents the physical world. A potential source of misconceptions is the existence of concepts closely related to DTs, such as simulations, the Internet of Things (IoT), and cyber-physical systems (CPS). [9] The confusion arises from these concepts being components of DTs. Certainly, the overlap between Industrial IoT and DTs can be considerable due to the significant overlaps in technologies. The confusion between DTs and CPS is more fundamental as many of the physical entities for which a DT may be created will be CPS. [9]

In the manufacturing world, a CPS is used more to maintain the operation and control functions of the system rather than being a digital representation of the system. This is best outlined in the paradigm of Industry 4.0, CPS is defined as systems of collaborating computational entities that are in intensive connection with the surrounding physical world and its ongoing processes, providing and using, at the same time, data-accessing and data-processing services available on the internet [10]. Embedded computers monitor and control physical processes, usually with feedback loops, where physical processes affect computations and vice versa [11]. These new autonomous systems are capable of elaborating and communicating data and building a copy of real processes in a digital environment in real-time.

4. Remote Collaboration in DT Application

One of the components of the proposed DT will be remote collaboration. This remote collaboration will enable anyone on the team to be anywhere in the world to monitor, maintain, and even improve upon the DT. This will also be a unique aspect of the DT due to there being limited literature. Most literature revolving around this topic is about how cloud computing can be leveraged to handle the computation of the DT. The reason for this is that cloud computing offers prominent levels of flexibility, computation power, and customization.

DTs and cloud computing can be used to better serve content to learners. The digital twin-driven system framework for end-edge-cloud collaborative network environment is designed, where it operates over three parts, that is, the end user, the edge cloud, and the core cloud. To better support the collaboration among them, four main modules are designed, which are the DT component, the content popularity prediction scheme, the content caching scheme, and the routing scheme, respectively. Based on the four main modules, the overall workflow can be described as follows: firstly, the DT component collects the related information from each edge server, and the corresponding statistic process is executed; secondly, the edge controller sends the collected data to both the core cloud and other edge controllers; lastly, the core cloud regards these data as parameters for both the content popularity prediction scheme and routing scheme. Specifically, the former uses the statistical data uploaded by each edge controller to construct and train the prediction model to periodically predict the stored data popularity, while the latter uses these data to calculate the optimal routing path for efficient content delivery. On the other hand, the other edge controllers rely on using this data to reach a simple consensus, based on which these edge controllers can easily collaborate to find the most balancing and efficient caching policy [12].

This section is concluded with discussion about the manufacturing service network DT in a Cloud Computing Environment. The manufacturing service network is a collaborative value creation network that integrates manufacturing and service functions, which through the mutual service of manufacturing resources between enterprises, gathers and integrates a network relationship, and directly provides certain resources and activities to help customers solve short-term or long-term problems. In a typical cloud computing environment, the DT system is a type of service-oriented networked intelligent manufacturing system. Based on the characteristics of the DT system, the definition and connotation of the DT network and the manufacturing service network, this paper defines DT as based on virtual and real interaction integration mode to integrate simulation, calculation, feedback control, and other functions and can realize the collection, mapping, and control of virtual and real resources. The DT system manufacturing service network is a type of interactive mapping network system oriented to manufacturing service collaboration, which is composed of physical entities, virtual models, service computing network nodes, the mapping, computing, and control connection relationships between each network node [13].

5. Digital Manufacturing

Sheet metal panels with multiple curvatures are desirable for a range of applications. English Wheel (Fig. 2 [14]) is a metalworking tool that squeezes sheet metal between a top and bottom wheel while an operator drives it through a path, promoting local stretching in turn giving rise to curvature. While both wheels can roll in place, the vertical height of the upper wheel remains fixed while the vertical height of the bottom wheel is variable. Recently, the process has been outfitted with a robotic arm. To create a DT of this process a virtual representation of the English Wheel, robotic arm, and sheet metal with the same dimensions as the physical world parts. The bending of the metal is done in Rhinoceros 3D software.

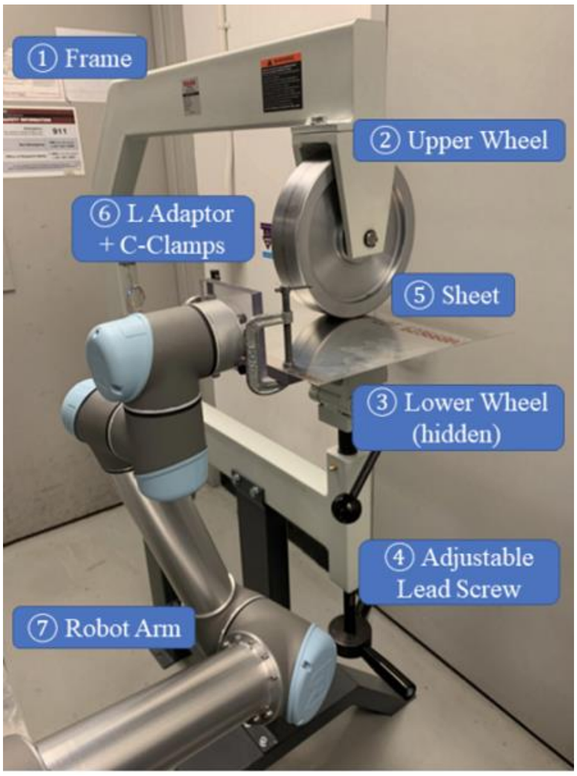

Fig. 2. English Wheel *[14]*

The robotic arm and control commands can be communicated through both offline programming and real-time control communication via RoboDK simulation software, as shown in Fig. 3 [14]. Offline programming can be achieved by programming script files in the UR Script programming language that can be directly uploaded to the UR5e processor and converted into UR5e readable .urp execution files. Real-time robot control communication is achieved by connecting the UR5e robot to the host computer via an Ethernet cable. Once the connection is established, robotic commands in the UR Script programming language can be sent directly to the robotic arm for command executions via RoboDK simulation software [14].

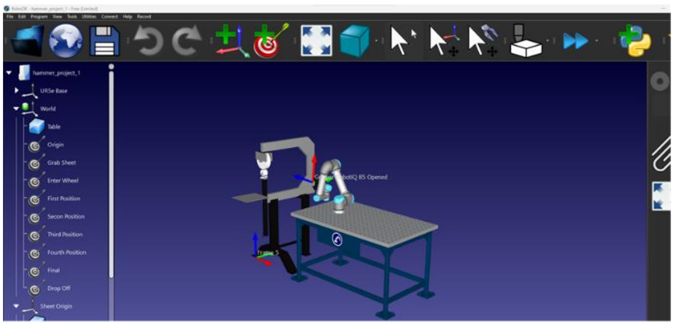

Fig. 3. RoboDK Simulation Example

As a second example, there was another team that used robotics for metal sheet folding. They completed two different folding projects to study the effects of the different design and fabrication factors. The main goal motivating these projects was the development of a non-load bearing hanging outdoor canopy. Although the projects had different geometric designs, they both used the same material, tools, and environment setup for fabrication. The design intent for these projects, and thus their geometric designs, dictated two approaches to the folding process. The first focused on tool programming. A 3D geometric form was designed in advance, and the fold sequence and robot tool path were generated to realize that exact geometric form. In the research from Dr. Sharif the material programming was addressed [15]. This was a reciprocal exploration of form generation, material properties, and robot movements, the goal of which was to reduce the need for meticulous fold sequence planning.

One Kuka robotic arm, a KR Quantec Pro (KR 120 R2500) with a payload of 120 kg and arm reach of 120 cm, was used for both projects. The robot arm was equipped with a Schunk pneumatic gripper. As the sheet metal folding process requires at least two grip points, we designed and fabricated a fixed grip system with two double-acting air-powered vises connected by two 12 mm steel plates. These pneumatic vises were linked to the Kuka robot's digital outputs so that they could be controlled via the Kuka robot language (KRL) code. This setup limited the part size to an approximate maximum of 100 cm in length. To generate the robot's toolpath for the folding sequences, we used the Kuka|prc plugin for Grasshopper 3D, a graphical algorithm editor. The digital outputs for the control of both the Schunk gripper and pneumatic vises were also programmed by Kuka|prc, which was embedded in the final generated KRL code for controlling the robot [15].

Another study used robots in the additive manufacturing process. Here, the full potential of a UV-DIW setup coupled with a 6-axis robotic arm is exploited. A customized graphic interface is developed allowing control over the printing parameters and the robot's relative positioning to the nozzle end. Regular octet lattices made of photo-curable ink are fabricated. The freeform ability of the system is assessed by evaluating the ink rheology and curing behavior as well as the samples matching with the digital file. The enhanced mechanical properties of the fabricated lattices are tested through uni-axial compression and compared with layer-based lattices fabricated via DLP [16].

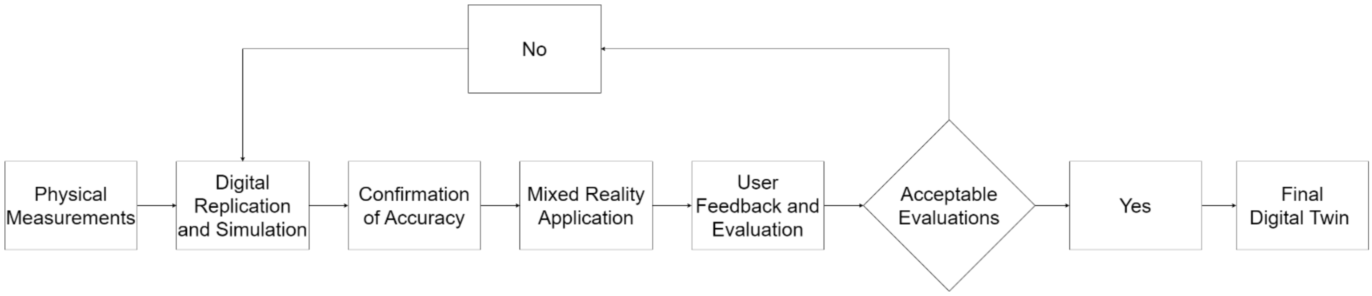

Fig. 4. Digital Twin Model Development Diagram

6. Human-Computer Interaction (HCI)

HCI is the study of how humans interact with computers. The interaction between people and computers takes place everywhere in everyday life through information processing. As the degree of contact between humans and computers continues to increase, the cognitive burden of interaction between humans and computers increases as the operating error rate increases. HCI scientists examine and create technology user interfaces. They research and enhance technological development processes and develop and assess new technological applications. HCI has gradually merged its scientific interests to improve the usability and technical understanding and technique of computer systems [17].

Sometimes called Man Machine Interaction or Interfacing, the concept of HCI was automatically represented by the emergence of computers, or more generally machines themselves. The reason is that most sophisticated machines are worthless unless they can be used properly by men. This basic argument simply presents the main terms that should be considered in the design of HCI: functionality and usability. The functionality of a system is defined by the set of actions or services that it provides to its users. However, the value of functionality is visible only when it becomes possible to be efficiently utilized by the user. The usability of the system with a certain functionality is the range and degree by which the system can be used efficiently and adequately to accomplish certain goals for certain users. The actual effectiveness of a system is achieved when there is a proper balance between the functionality and usability of the system [19]. Thus, the overall goal of HCI is to make the interaction of humans and computers usable and reactive to human needs.

As an important part of the human-machine systems, the HCI is a key point of the design activity of the systems, whose existence is not the task itself, but in the real situation of HCI to achieve the mutual communication and establish the mutual platform between users and machines, by which to realize the operation on the machines, namely, designing input and output ways of information, thus to achieve a sound function of HCI. Hence, the key to the design of the interface lies in on how to achieve a perfect and harmonious HCI; only in this way can the cognitive load of people be reduced fundamentally and enhance the apperceive and operation abilities of users. For the users, the interface is the system. Simply speaking, an interface is composed of a control panel consisting of a display and controller, a touch screen incorporated by controlling and displaying, a software interface, and many kinds of interfaces that may be used in some complicated products or systems. The process of HCI is a process of inputting and outputting information. Through HCI, users send instructions to the computer, and then the computer presents the results to the users after calculating and processing. The input and output modes between humans and computers are various, so interaction modes are diverse, including data interaction, figure and image interaction, voice interaction intelligent interaction, etc. [20].

7. Research Methodology

To build out the English Wheel DT used in this project a series of steps needs to be taken. The first step is getting the physical measurements of each machine and sheet being used. By getting the physical measurements the digital replication can be exact. Next, to replicate the machine measurements and movements inside a digital simulation Grasshopper3D was used. After this, confirmation of the accuracy of the digital simulation is needed. This is so that the digital simulation is a one-to-one match of the real-world machine and the machine's movements. After confirming that the digital simulation is identical to the real world, the MR application is implemented. With Grasshopper3D, there is an extension that can streamline the process of creating an MR application. The reason for implementing this extension is that MR will give a greater level of immersion to the user. The last step for this DT application is to get user feedback and evaluations. The goal of getting user feedback is to improve the user experience and usefulness of the DT. The process is outlined in Fig. 4 and is delved further into in later sections.

7.1. Physical Measurement

To build a DT, physical and digital objects must match. If the measurements are not aligned properly, then the simulations for the digital side of the DT will be inaccurate and cause improper decisions to be made. The exact measurements of the physical components were given by the manufacturer of the English Wheel. This was also double-checked by the researchers at Northwestern University since that is where the physical robot and English Wheel are located. The robotic tool path created in UR script that came from the NU team.

7.2. Digital Replication and Simulation

With physical measurements and robot tool path, digital replication and simulation can be designed and implemented. The replicating and simulation of the machine was made in the simulation software called Rhinoceros 3D (Rhino). A software inside Rhino called Grasshopper3D (Grasshopper) was used to replicate the English Wheel using the modeling tools that Rhino offers like the surfaces tool, as seen in Fig. 5. This tool makes a surface only from 3 or 4 points or curves in the software. Also in Rhino, a script can be created to make the digital representation of the English Wheel move just like the physical representation.

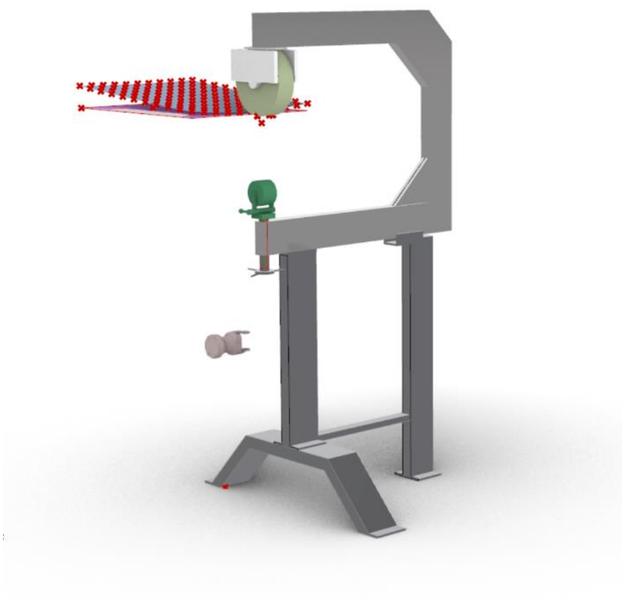

Fig. 5. English Wheel Digital Representation Inside of Grasshopper3D

The robotic arm was recreated in the Grasshopper software based on a free-use robotic arm online model. The robotic arm movement was created using the algorithm editor that is used in Grasshopper. Fig. 6 are the components that were used for the robotic arm script. In the script, there are multiple groups of components. The reason for this is that some groups control just the robot while others control the metal sheet and the interaction between the metal sheet and the English wheel. The main component, which is shown in Fig. 6, controls the robotic arm. To control the robot there is a robot loading component that will load the geometries of the robot. From there the robot arm is placed at the end of the sheet to replicate the physical robot arm placement. This is done using a target point component. With the robot arm loaded and the target point located, the next component is to create the program component. This component is used to test the program and see if any common errors are present in the script. The final component that is being used for the robotic arm is the program simulation component. The program simulation component takes the output of the create program component to create the rough simulation for the script. A time variable is also being used to ensure that the simulation is visually like the physical robotic arm.

The next steps in building the DT model were to make sure that the bending of the sheet metal was correct. This is an especially important part because this is part of the physics of digital simulation. Hence, to have accurate results, an accurate measure of the sheet metal was needed. The sheet metal was created in AutoCAD 3D. AutoCAD was the simplest and easiest tool to create this simple 3D object with precise measurements. After creating the sheet metal in AutoCAD, the sheet metal was imported into the Grasshopper project.

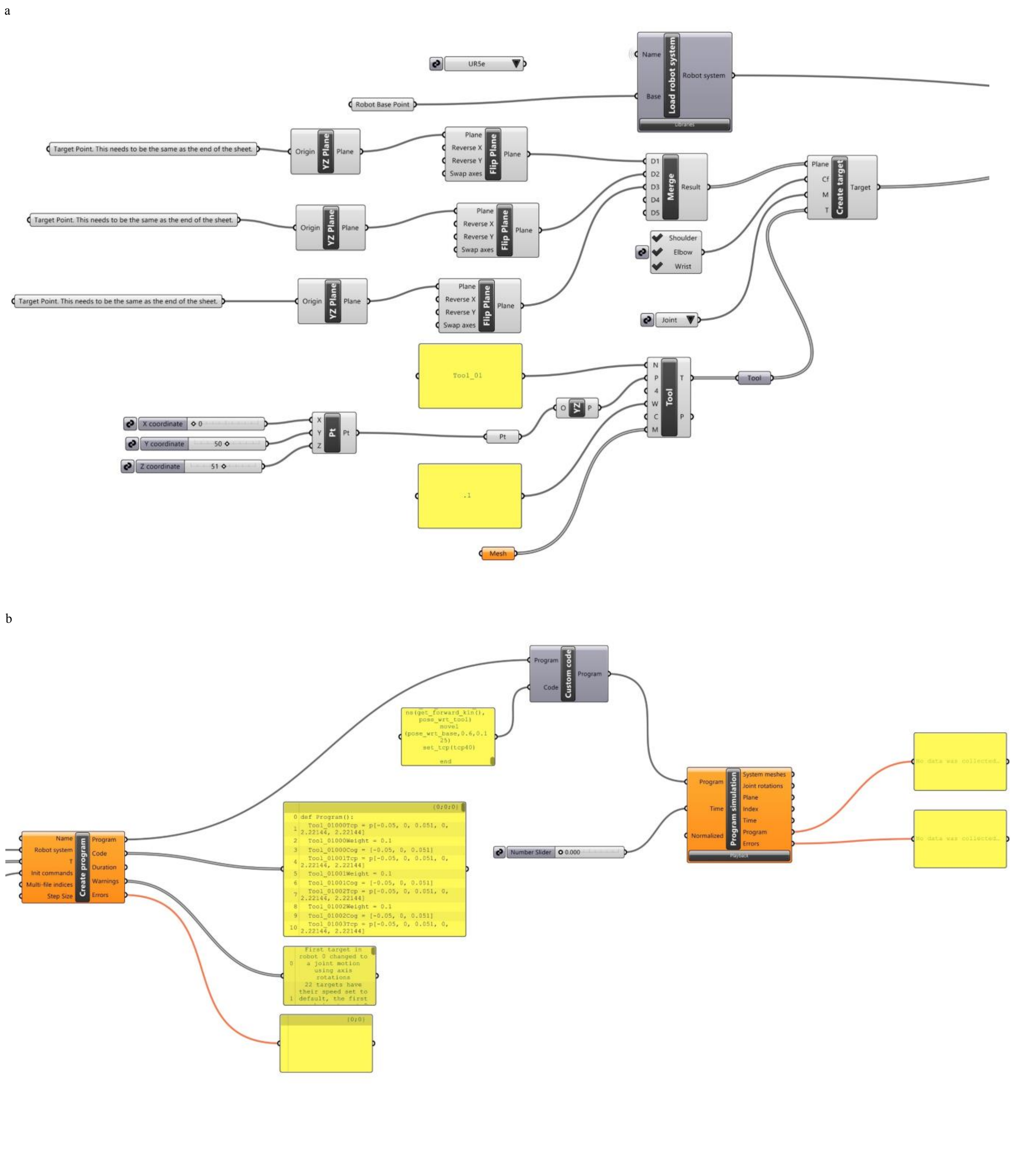

Fig. 6. (a) Components to handle the robotic arm movements, (b) components to handle the simulation

7.3. Confirmation of Accuracy

The last step of setting up the DT is the confirmation of the accuracy of the digital simulation. This confirmation will happen in several ways. The first way is visual confirmation. Visual confirmation will comprise of visually making sure the robotic arm in the digital simulation moves the same way as the physical robotic arm. Also with the visual confirmation step, a confirmation of the measurements of the English Wheel machine, robotic arm, and metal sheet will once again be checked for accuracy. The second way of confirmation will be curvature measurement of the digital metal sheet. The way this will be done is calculating the curvature of the digital metal sheet after the simulation runs. This calculation will be checked against the physical metal sheet curvature. If both measurements are similar with a very low difference in measurements, that means the physics in the digital simulation is running correctly. After the confirmation of the accuracy of the DT, the next step is to build out the MR component.

7.4. MR Application

The last step that needs to be discussed is the Fologram component. Fologram is a necessary component to view the Grasshopper simulation on Microsoft HoloLens. In other words, this component is what gives the DT the MR application. The way Fologram can work is by connecting the geometry from the other Grasshopper components and streaming that information to Microsoft HoloLens. As an example, for this project the geometry for the robot arm movement can connect to the Fologram component so that on the HoloLens the user can see the movements. In other research projects, Fologram has been used for visualization of industrial robots in construction. This research team used Fologram to predict the manufacturing process of the different robotic designs.

7.5. User Feedback and Evaluation

With the digital representation of the English Wheel, Sheet Metal, and Robotic Arm now accurately matching the form and function of the physical representation of these objects the next part of the DT, which is the bidirectional communication. An overview of bidirectional communication is as follows: any decision made in the physical world is reflected in the digital representation and the digital simulation gives an accurate digital result. For example, if there needs to be a change in the wheels for the English Wheel to see if there would be any better results of bending the sheet metal. The digital model would include this update as well as the updated physics for this new wheel, after which would produce a new result. The new result would then be shown in physical space using the MR application of this research project. This would enable anyone who wants to view the results of simulation in the physical space to get a true understanding of the results. Thus, with this example, the bidirectional communication of the DT is shown.

To make sure the DT produces these accurate results an evaluation of the model will be conducted. This evaluation process will consist of two sets of tests. The first test will be simple user feedback of the DT model. To get user feedback, a series of questions will be asked to see how the user felt about the DT in key areas such as ease of use and accuracy of the digital representation. The second set of tests of the DT is to get eye-tracking data from the user. This will be done when the user is using the MR application of the DT. The reason for this test is that it will produce valuable data about what the user is most focused on in the MR application.

8. Discussion and Conclusion

With the growing field of DT technology, it is obvious that there will be differences in definitions and what comprises a DT. In this research, it was determined that there is a commonality of all the different definitions and components. So, the definition of a DT that is being used in this research is that a DT is technology that has a one-to-one digital representation of a physical system that also has a bidirectional communication between the digital and physical representation for predictive control, and model updates.

The DT framework in this research also has an additional component of having the interactions inside a MR application. MR is where the digital components are overlaid into the physical world but also can have interactions with the physical world. This is different from other extended realities such as virtual reality since MR could interact with the physical world. Thus, this gives MR a level of immersion that virtual reality and other extended realities cannot achieve.

The level of immersion that MR is crucial to this project. This is because digital objects are overlaid into the physical world. With this it would give the user a deeper understanding of how the robot interacts with the physical world. Also, with MR there is a way to achieve remote collaboration. Remote collaboration can happen since the remote collaborators will have the same simulation and see the exact simulation with the user. Thus, making it possible for teams working on the same simulation to be in many different places.

To build out the DT framework in this project used Grasshopper3D and AutoCAD. Grasshopper3D was used to handle the digital simulation of the DT. This was done by using the components in Grasshopper3D scripts. Different components handled things such as the movement of the robot arm and creating the MR application. AutoCAD was used to create a one-to-one representation of the metal sheets that are being used to bend in shape using the English Wheel.

This leads to the future of the framework. This framework will be used to build and complete a functional DT. The future idea of the DR is where there will be a predictive model for future prediction or a bidirectional remote collaboration communication. The predictive model implementation will consist of AI in the MR environment. This development will be used to create predictions on certain variables for the manufacturing process which will aid in predictive robotic manufacturing control. An example of this on the English wheel where the pressure will be applied on the sheet, and displacement will be predicted. With these predictions, it will be possible to create an optimal path for the robot to create the exact sheet an operator would want, which would also reduce the waste of material and time. Bidirectional remote collaboration communication is a concept where the data and commands for the robot will be in a cloud environment. A Rhino3D plugin could then be used to retrieve the data commands from the cloud. After retrieving the data, Fologram could then display the information in MR and the user could then make any modifications to the commands to fit the desired outcome. After any modifications that the user made would be sent back to the cloud to where the robot would execute the new commands. Thus, this will enable any team member across the globe collaborate in any future manufacturing efforts.

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