Real-time Digital Twin of On-site Robotic Construction Processes in Mixed Reality

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Abstract –

The use of robotics in construction improves safety and productivity in construction sites. However, there are limitations for construction managers to monitor robotic construction processes. This is due to the lack of well-developed human-robot collaboration interfaces. Digital Twin (DT) and Mixed Reality (MR) are two emerging technologies that can help to address these limitations by enhancing human-robot interaction, for on-site construction processes. However, DT in MR for human-robot interactions in robotic construction processes has not yet been widely studied in research or in practice.

This work explores effective human-robot collaboration for automated construction processes using on-site real-time DT of robotic process in a MR construction environment. First, a DT prototype of a robotic construction process establishes a two-way communication between the physical and virtual models of the robot arm. Next, real-time process data is collected from the robot and sent to the visualisation and database platforms. This work describes the workflow in order to send the real-time data to the MR headset for direct visual feedback and direct interaction with the robot arm. The prototype is validated using a case study demonstration of a robotic masonry construction process.

By demonstrating this proof of concept for real-time DT of robotic construction processes in MR, this work contributes to construction management for digital fabrication through human-robot collaboration. This work concludes with potential future research directions including data access and manipulation for digital processes in construction sites.

Keywords –

Robotics; Mixed Reality; Digital Twin; Human-Robot Collaboration; Real-time visualisation; Digital Fabrication, Augmented Fabrication

1 Introduction

The construction sector ranks almost the lowest in digitalisation amongst many other industries [1]. Research in digitalisation of the industry is needed to improve the current process of construction. One such digitalisation approach is the use of robotic technology. Recent research explores robotic technology to integrate design and construction processes and their adoption in the scale of industrialised construction [2].

Robots can be used for various repetitive and dangerous tasks [3]. The use of robots requires a better feedback loop between humans and robots for collaboration in design and construction processes [4]. Digital twin is an emerging technology to improve human-robot interaction for collaboration in construction [5]. The state-of-the-art digital twin concept in construction is described by Sacks et al. [6] as the "construction twin," or in other words the twinning of the construction process. In the case of digital fabrication, when the construction process is undertaken by robots, the digital twin of robotic construction refers to the twinning of the robotic process.

Conventional robotic processes in the construction industry follow the workflow as shown in Figure 1. For the execution of a robotic process, first a code is written. The required data and the code are then sent to the robot for execution. The robot follows the commands as written in the code. Finally, the physical robotic task is completed. After the execution, a user inspects the commands procedure and creates a feedback loop by editing the code and sending it to the robot again.

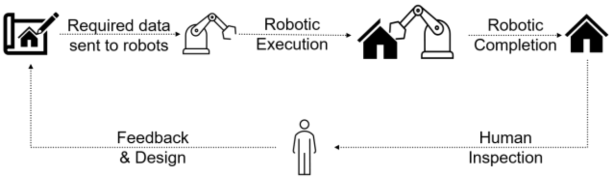

Figure 1: Conventional feedback loop

However, this conventional feedback loop is relatively sequential and real-time feedback is not supported during the robotic construction process. This can be improved by a cyber-physical real time DT throughout the process [4]. DT enhances computational abilities and provides a collaborative system [5], [7]. Although DT can improve the collaboration, construction workers require the feedback to be in a visual format to better understand and respond efficiently [8]. This work proposes an alternative feedback loop that integrates information throughout the processes, while augmenting virtual feedback using DT and immersive visualisation in MR. The data produced in the process is stored in a database to use for future purposes such as progress monitoring or process automation. The proposed feedback loop is shown in Figure 2. It allows users to communicate with the robot in a much more efficient way. The proposed DT allows a two-way communication between the robot and the human to improve the effectiveness of the collaboration during the process.

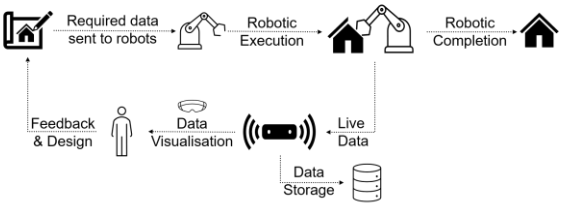

Figure 2: Proposed feedback loop with DT in MR

2 Literature Review

This section explains the following four topics in recent research:

- Robotic construction
- Digital Twin (DT)
- Spatial Computing in Mixed Reality (MR)
- Data Management

2.1 Robotic construction

In construction, it is often challenging to use robots on site because many construction sites are unstructured and dynamic [9]. On one hand, robotic construction can save time, improve geometrical accuracy, reduce construction cost and improve site safety and human well-being [10]. On the other hand, it requires specific robotic expertise and information integration to operate robots on-site [11]. This can be improved by the use of dedicated sensing devices to improve the feedback loop [12].

Robotic technology has been adopted in the construction industry for many applications, such as drywall installation, painting, welding, bolting, drilling, pouring concrete, masonry, façade installation, 3D printed formwork and external walls, timber structure assembly and autonomous anchoring [10], [13]–[17]. Construction robots often involve discrete interaction between human and robot during the robotic construction processes. For example, the feedback of scanned data has been used for robotic design and construction of timber architecture [19]. This can lead to safety issues, especially in a dynamic environment on the construction site [18]. The industry requires a more interactive and immersive feedback loop such as using sensing devices for humans to interact in real-time with robots [12].

2.2 Digital Twin (DT)

DT was first proposed by NASA to a novel "paring technology" to connect the real world and cyber world. It can increase the cognitive abilities towards intelligent and autonomous systems. DT has been used in various contexts by many researchers and industries.

DT for construction follows the twin of the building rather than the process. The DT as used in construction is described by Tao et al. [21] as a representation of three main elements: the physical element, the digital counterpart and the connecting link [6], [21]. It is referred to the Building Information Modelling (BIM) model as well as the data generated in the operational phase [22]. However, its foundational concept has not yet been well defined for construction processes.

Different from DT, the digital shadow represents a one-way communication to the physical representation; whereas, DT represents automatic two-way communication between the physical and digital environments. DT can be classified into two types - Product DT and Process DT [23], [24].

2.2.1 Product Digital Twin (DT)

Product DT refers to the twin of a physical asset, where the asset's properties and behaviour can be represented in digital form through modelling, analysis and simulation [25]. The difference between the digital model and the digital twin is the connection between the physical and digital models [26]. In the construction industry, product DT is often referred to as the digital asset of the building in the operational phase. It consists of the BIM model of the building together with live integrated data modelled with semantic relationships [27].

2.2.2 Process Digital Twin (DT)

Process DT refers to the dynamic behavior of the operation conducted with the physical counterparts to achieve real time synchronisation between the digital and physical environments. In a process environment, such as manufacturing, a digital twin would be used for monitoring, control, diagnostics and prediction[28]–[30].

Such a real time synchronisation of data can lead to efficient human-robot collaboration with virtual and physical objects. This facilitates innovative approaches for design, validation and control of the robotic processes [31]. DT can also be used for product life cycle management [21]. The process DT twin in the manufacturing industry is used to improve the human-robot collaboration using head mounting devices. Process DT includes the following properties [26]:

- Simulation of robotic process
- Two-way communication with robot
- Real time monitoring of sensed data
- Data storage for future

However, to date, there are few examples of process digital DT for construction robotics.

2.3 Spatial Computing in Mixed Reality (MR)

MR is the augmentation of virtual objects in the real world that can be visualised with a head mounted device. This allows users to see the real world as well as the virtual objects that are embedded in the real world. Within the concept of MR, spatial computing creates an environment for communicating and visualising the spatial relationships of the real world [32]. This enables real time interaction between the virtual objects and the physical environment. Spatial computing can be used to make the virtual object interact with the real world. MR can be used to control the robots [33]. In the construction industry, MR can be used for safety collaboration, site survey, prefabrication, remote design, training for workers and facility management [34]–[36]. However, there is no defined application of MR in robotic construction processes.

2.4 Data Management

Huge amounts of data are created in digital processes. Data in the DT of construction processes can be used for process tracking and project monitoring purposes [6]. The data here refers to the live data obtained from the DT, which can include any sensor data that is obtained in real time.

Available databases for data storage can be relational or non-relational. A relational database is often in table format. These are commonly used by Civil Engineers in .csv format so that it can be imported to Autodesk® Revit for scheduling or quantity takeoff purposes [37]. Relational databases are not highly scalable; often this data structure gives rise to high complexity as data cannot be easily encapsulated in a table [38]. The creation of a DT for construction robotics requires multiple sources of data from various sensing technologies. Thus, there is need to explore of non-relational databases in construction DT to accommodate data from multiple sources.

Data obtained from DT can be used for various purposes such as optimising the process that is being executed by making the robots process aware. This can be achieved by creating semantic data relationships to open up intelligent semantic platforms (referred to as Generation 2) and agent driven socio-technical platforms (Generation 3) of a Construction Digital Twin [27]. Furthermore, an ontology-based communication can be used in a standardised way for data transfer [39].

3 Workflow

Figure 3 shows the proposed workflow for the DT of robotic construction process in MR.

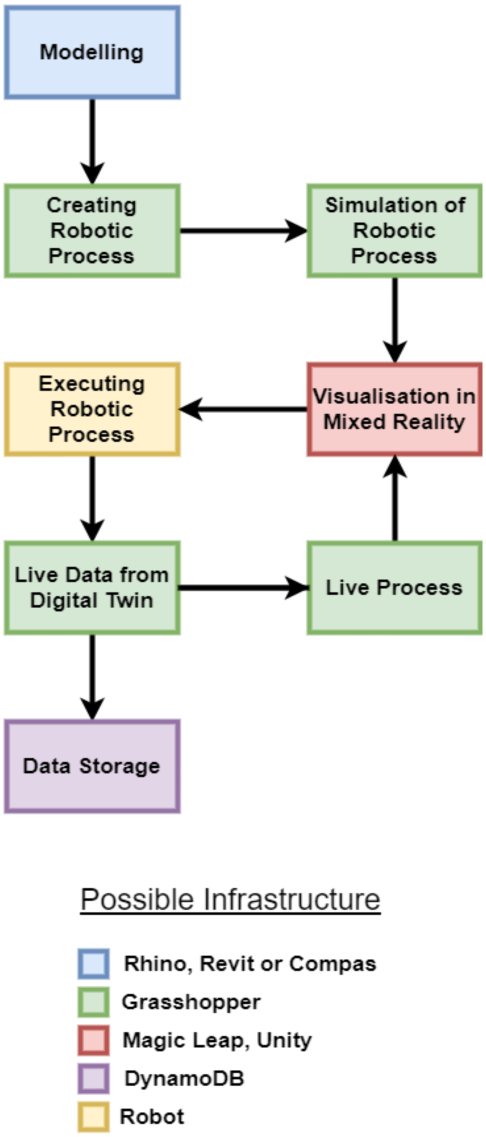

Figure 3: Workflow of the DT of the robotic construction process in MR

This workflow represents the procedure that is required to be followed for any robotic construction process. The process includes design, robotic operation, visualisation in MR and data storage.

Design is the first step in a conventional construction process. The required data from the design is filtered and sent to the robot, depending on the task that the robot would perform. The level of detail of data sent to the robot depends on the geometrical information required for path planning, to define the robotic process. Path planning represents the local navigation of a robotic system. The robotic process can be simulated and visualised in MR prior to sending it for operation to the robot. Any change in design can be altered during the robotic process and visualised in MR. Further, the data during the DT process is stored in a database, which acts as a log that can be used for process monitoring purposes.

4 Validation and Findings

To verify and validate the proposed workflow in Figure 3, a prototype of a robotic masonry construction process for a robotically fabricated wall is conducted as a case study.

4.1 Masonry Construction

4.1.1 Modelling

First, the masonry wall is modelled using computational design as shown in Figure 4. The bricks are modelled as mesh objects in Rhinoceros 3D (Rhino)®, along with the information of the plane at the midpoint of each block. A reduced scale of 1:2.5 of the standard brick size is used. The width of the brick must lie in the tolerance value of the robotic pickup tool. The data extracted from modelling for robotic execution are the midpoints of each brick along with the plane of orientation and the width of each brick. In the Grasshopper script, each plane representing the midpoint of the block is stored in the plane component. This component is connected to robotic execution for the "Place location" of the brick

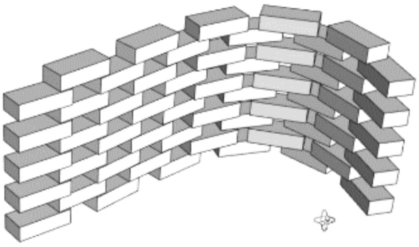

Figure 4: Wall model in 3D

4.1.2 Robotic process

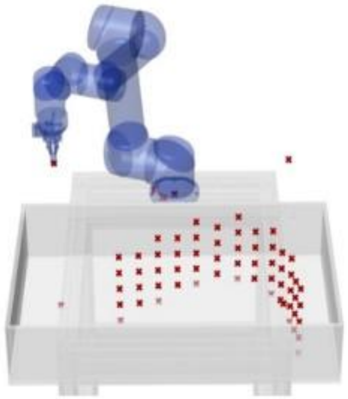

Figure 5: Robotic path planning

The robotic process involves path planning of a robot for the masonry work. The Universal Robot 5 (UR5) was used for the prototype. The robot can be seen in Figure 6. The path of the robot follows repetition of the picking and placing of the bricks. The path is visually coded using the Robots plugin in Grasshopper. Figure 5**Error! Reference source not found.** shows the points of placing the brick along with the pickup point. Once the path is simulated and is ready for execution, data can be sent to the robot through LAN connection to pick up bricks at a dedicated location. The execution follows the path shown in Figure 6Figure 6. The following steps are shown as follows:

1. Unobstructed point above pick up location
2. Pick up location
3. Unobstructed point above pick up location
4. Unobstructed point neat place-location
5. Place point – obtained from model
6. 30mm above place point
7. Unobstructed point neat place location

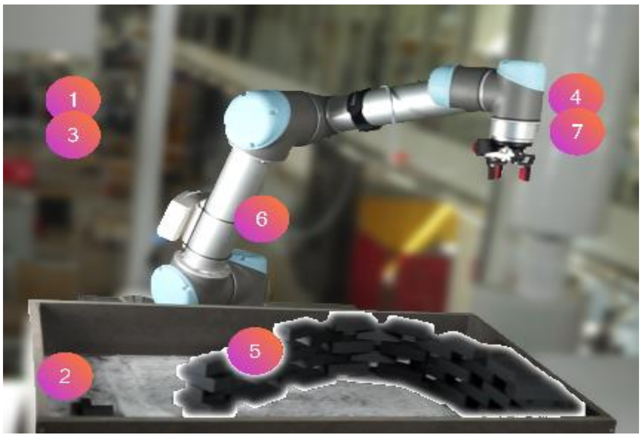

Figure 6: Robotic Positions

4.1.3 Visualisation

The simulation and the live data obtained from the Rhino Grasshopper are visualised in the MR. The mesh data is sent as a game object from Grasshopper to Unity® using Rhino®. Inside.Unity and visualised with the MR headset using Zero Iteration. In this work, Magic Leap headset is used for visualisation. It allows users to monitor the entire process of simulation and the robotic operation. Visualisation of the simulation in MR is a step for *Virtual Commissioning*, which is used to simulate the expected manufacturing systems and control programs prior to execution of the physical system. This simulation visualises both the robot and the robotic process in the real place on-site [33]. After sending the robotic commands, the live position of the robot is obtained for visualisation. This visualisation allows the user to live monitor the process. Figure 7**Error! Reference source not found.** shows the live position of the robot as well as the mixed reality parallel to each other. Also, the robotic process can also be monitored and controlled remotely using Magic Leap® MR control tools.

Figure 7: Real and Virtual display

4.1.4 Data Storage

The live positions of the robot are recorded each second from Grasshopper and sent to Dynamodb using Amazon Web Services. The current data includes the angle of each joint of the UR5. In future, if more sensors are added for monitoring in the construction process, the items can be added directly to the Dynamodb database for storage. Each element would be represented in a well-defined format as explained below. This format can be used for all future projects.

{“Time": "05/09/2021 16:54:06",
"Type": “Robot”,
"Robot":
{
“FkInput": "3.699685| -1.825343| -1.045692| -1.842495|1.57278|3.701816"
} }

The "Time" attribute represents the time of the sensor data received. It also acts as the primary key to the database, which means all the values are unique. The "Type" attribute represents the information of the type of sensor that is being used. Here, the sensor is directly from the robot and thus has the value of "Robot". The technology is represented by "Robot" attribute. The value corresponds to the data obtained from the robot. In this the value represents the angle of each joint of the robot at an instance of time. The robotic configuration of UR5 can be reconstructed using this value. For other sensors, the attribute changes to the corresponding sensor information retrieved.

4.2 Discussion

4.2.1 Potential Applications

1. Process Monitoring

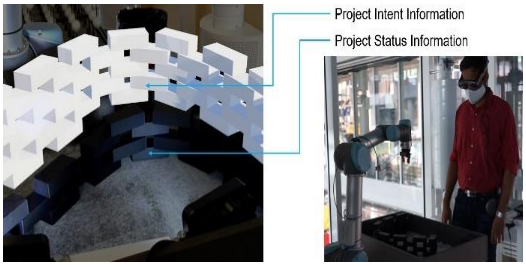

Figure 8: Process monitoring

Construction managers can use the proposed workflow for process monitoring as proposed by Sacks [6]. The project intent and status information can be obtained from the visual information seen in mixed reality. This information can be used directly by the users to monitor, control and update the real-time progress of construction in DT. Reality capture can also be added as one of the sensor inputs to be used for progress monitoring management [20].

Furthermore, digital fabrication engineers can use process monitoring to compare the intended information to the actual completed process. This can help when material behavior is not well known. For example, the application of materials such as concrete, fabric etc. where the material properties are not rigid and are not easy for simulation.

2. Remote Monitoring

Construction managers or project owners can use the proposed workflow to monitor the process from a remote location, away from the construction site, as shown in Figure 9**Error! Reference source not found.**. Managers can simultaneously monitor different zones or locations of the construction site enabling them to multitask more efficiently. For project owners, the progress of the construction can be monitored completely remotely. It gives the owners an opportunity to know the status of construction while remaining in an office far away from the construction site.

Figure 9: Remote monitoring

3. On-site virtual commissioning

Digital fabrication engineer can use real place virtual commissioning as a pre-check in the construction site, before the execution of the robotic process [40]. The robotic process can be checked on the site using MR. This can help to avoid collisions within an unstructured construction site as well as avoid the bottleneck of activities due to uncertainty in execution. This virtual commissioning can also facilitate coordination amongst the project teams – in particular the digital fabrication design coordinator – to comprehend and incorporate digital fabrication requirements during design development of the design process [41].

The proposed use cases for various project roles are summarized in Table 1.

Use Case	User	Application
Process monitoring	Construction manager	Live status update
Process monitoring	Digital fabrication engineer	Live monitoring of intended and executed details
Remote monitoring	Construction manager; owner	Remote monitoring of multiple projects
Real-place virtual commissioning	Digital fabrication engineer	Precheck of the process before execution
Real-place virtual commissioning	Digital fabrication Design coordinator	Incorporate digital fabrication requirements in design development

Table 1: Potential applications

4.2.2 Limitations and future research

The digital fabrication process is dependent on the type of task done by the robot. Each process requires specific input and process development. The validation of the workflow was done using the masonry wall construction. In brick masonry, the geometry of the wall with the mid-point and plane data of each brick is necessary and sufficient data for robotic construction. The robotic execution is a process-orientated setup. Each type of function would require basic understanding of the function to be performed by a human. This will help in creating a better human- robot collaborative environment. The details in each robotic process are unique to its application. More research is required to study the process as well as consider what technology would be required to sense the monitoring process, with the potential future development of a holistic framework for real-time DT of on-site robotic construction processes to be visualised in MR.

The currently used MR headset had a least count of 100mm, whereas the robot has a least count of 1mm. This means any value between 51mm and 150mm for the robot would correspond to 100mm if measured using MR. Thus, the spatial information from the MR in this workflow cannot be sent to the robot for execution of the process. Future research can be done to improve the sensor accuracy of the MR device. If required, an external sensor can be added to the DT to measure distance more accurately.

The data used in the DT process is directly extracted from the robot. In future research, more sensors can help in better feedback of the robotic process. The database created in this research allows the addition of data from multiple sensors of any type. More research is needed to determine which sensors should be added and the relevant data required for the process.

The data is stored using the Amazon DynamoDB database. The database needs to be filtered and queried according to the use case. The current approach lacks semantic relation to the entities. With the addition of more sensors, the structure of data should be supported by the creation of ontology to show the execution of the process.

5 Conclusion

This work combines state-of-the-art research on robotic construction, DT, spatial computing in MR, and data management to propose a workflow for a DT of robotic construction. The DT is visualized in a MR prototype using multiple computational design platforms. The workflow is validated using a brick-laying construction process that uses a UR5 robot arm. The prototype demonstrates how the workflow enables a real-time DT of robotic processes for on-site construction. This work discusses three potential use cases of the prototype – process monitoring, remote monitoring, and real-place virtual commissioning – in construction including potential users and their applications. Moreover, this work illustrates the limitation of this research and the potential lines of future research.

Overall, this work contributes to the body of knowledge in construction twins and construction management using MR technology. Based on the findings, DT helps to improve collaboration for human-robot interaction and enable remote control, monitoring and real-time updates of the robotic processes using MR technology. Also, BIM-based DT of robotic construction in MR facilitates information integration and data management for digital fabrication adoption in design. Furthermore, the DT allows users to give the feedback to the robotic process in a more efficient way with an immersive environment for visualisation and human-robot interaction.

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