Implementation of an Augmented Reality AR workflow for Human Robot Collaboration in Timber Prefabrication

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Abstract –

In this paper, we present a set of enabling technologies developed for the KUKA Innovation Award to facilitate Human Robot collaboration targeted for the architecture, engineering and construction (AEC) sector. Critically, little progress has been made in the usability of user interfaces for industrial robots [1]. We targeted our investigation explicitly towards human-robot collaboration (HRC) in wood based prefabrication production. Although wood is a sustainable material with abundant processing possibilities, it is also a material system where process knowledge remains critically important, making highly automated workflows unfeasible and inefficient.

We propose an interactive fabrication process where a user such as a construction worker could wear an augmented reality head mounted display (ARHMD) as an interface to plan robotic trajectories, influence production sequencing, and view superimposed diagnostic feedback. We describe necessary system components including a robotic workcell consisting of a KUKA LBR iiwa, flexFELLOW mobile platform, a Robotiq 2-finger gripper and a custom platform and material feeding station. In addition, we describe a communication framework and set of protocols connecting a CAD digital design environment, a user interface (UI) for Microsoft HoloLens, a ROS server for backend path planning and coordination, and a 3D graphical web interface for downstream visualization of construction status. We conclude with an outlook on enabling technologies for human-robot collaboration in construction, and the importance of increasing digital integration and accessibility in characteristic production workflows through accessible and intuitive digital interfaces.

Keywords –

Human-robot Collaboration; Timber Construction Prefabrication; Robotic Fabrication; Augmented Reality; Digitalized Construction; Hardware-Software Interoperability

1 Introduction

The construction industry stands to benefit tremendously by increased digitization and automation [2,3]. Extensive progress has been made, primarily in research contexts, in the development of nonstandard material systems enabled through digital and computational workflows connected to physical and precise production equipment including industrial robots. However, there still remains a lack of transfer of these developments into typical production chains and construction processes.

Though there are many factors which have hindered the importation of robotics into construction, one reason is the need for human level dexterity and cognition due to the unstructured nature of construction tasks. In prefabrication workflows, where production occurs in a more structured setting, there is still often a need for human intervention in response to material inconsistencies. Existing timber construction methods and construction systems rely on the expertise, craftsmanship, and dexterity of human workers, favouring a “human-in-the-loop” production chain over highly automated production. Thus one way to increase efficiency and productivity is to facilitate collaborative human and robot workflows, where digital mechanisms and enabling interfaces can orchestrate safe exchanges of tasks.

1.1 Research Aim

Thus the aim of the project is to develop a set of technologies to facilitate an interactive human-robot collaborative workflow for the construction industry: where a user such as a construction worker with limited background knowledge in robotic programming, can interact with a robot system through an augmented reality (AR) interface. To investigate this question, a proof-of-concept fabrication system for human-robot collaboration is developed. In the developed workflow, production and assembly tasks alternate between a human user and the robot system in the construction of an architecture scale non-standard wooden construction system. Additional communication mechanisms increase interoperability with secondary devices and monitoring platforms.

2 Context

2.1 Challenges in Adapting Robotics in Construction

Much has been written about the construction industry's reluctance to embrace both digitalization and robotic technologies. Reasons given include the compartmentalization of the construction industry [4], interoperability of software for different services, and lack of accessibility of robotic technology as barriers for application. A standard fabrication systems including the well-known six axis industrial arm, developed for the domain of manufacturing, is additionally known to be ill suited for unstructured environments such as a construction site. In addition, historically, robots developed with specific use for the construction industry were primarily focused on narrowly automating single tasks, rather than automating many different tasks within a singular production workflow [5].

Though redesigning building systems for the contingencies and constraints of automation through integrated co-design processes is one long term solution, this project focused in particular on HRC as a means to accelerate automation of the construction industry in the short term.

2.2 Human-Robot Collaboration

Human-robot collaboration as defined in TS/ISO 15066:2016 is an operation where a human worker and a purposely designed robot system can perform tasks in a defined collaborative space concurrently during a production operation. From a technical point of view, this definition means mainly that the motor drives are powered (moving or in safe operational stop) and brakes are not applied even when the robot or its workpiece is in close proximity or even in a physical contact with a human.

However, manufacturing applications with standard industrial robotic arms pose serious danger to human workers and have to be equipped with additional safety components for a safe HRC which decrease the flexibility of the system and increase the setup costs. To overcome this problem an entirely new type of industrial robot arm and controller emerged in past years that can limit the collision forces and thus prevent harm to human body in the event of a contact. Though collaborative robots were developed initially with different target applications and domains, their safety in proximity to humans makes it possible to implement them in fundamental research where collaborative workflows are necessary. Construction sites, which are inherently unstructured, and existing construction systems that rely on human cognition and expertise, make the AEC sector an ideal domain for human robot collaboration.

While the issue of safety is an elementary part of HRC it is only one layer of behaviors needed for successful collaboration [6]. From a broader perspective collaboration does not involve only physical behavior of the involved agents but also their cognitive states [7] as well as optimal form of human-robot communication frameworks.

In this context, the proposed system focuses mainly on the design of appropriate interfaces between a human operator and the robot system resulting in a higher level of behavioral cooperation while limiting physical human-robot interaction. The system also involves only simple cognitive functionality and focuses more on increased integration and interoperability through a set of digital mechanisms connecting design and production.

Similarly, the topic of safety is addressed by others [8,9] and it is not focused in this paper.

2.2.1 Automation in Timber Construction

There are various reasons for the recent rapid advancement and relevance of HRC within the construction industry. The two main reasons are:

- The need to address the growing demand of product customization instead of standardized mass-production.
- Importance of increasing competitiveness of small and medium-sized enterprises (SMEs) that must usually rapidly adapt production to new products in small batches.

Typical construction industry projects can be characterized as a one-of-a-kind production with a fragmented supply chain (i.e. many different contractors involved) that are being fabricated mainly on-site [10]. In Germany, where this project was based, in particular more than 88% of the construction market is formed by companies with up to 19 employees. Timber construction and carpentry companies in Germany have those numbers even higher with more than 96% of the companies having up to 19 employees [11].

Timber construction has however several key features and differences that increase the chances of the industry to adopt novel automation strategies. Those features are especially:

- High level of off-site prefabrication in a controlled

environment
- Short required technological brakes during the production (e.g. glue setting)
- Easy to machine and assemble materials

2.2.2 HRC in Timber Construction

The Level of Automation (LoA) in timber construction is relatively high in the earlier stages of the prefabrication chain where the material is being shaped and trimmed by various CNC and power tools. On the other hand, the subsequent assembly stages that require higher flexibility and human knowledge are still largely manual.

Standard automation strategies developed as a result of flow production demands are not suitable for the dynamic batch and job production within timber construction prefabrication which requires flexibility. HRC applied towards prefabrication presents an opportunity to increase the automation and productivity of timber prefabrication by combining the human knowledge and dexterity (e.g. screw fastening) with the advantages of industrial robots (e.g. precise positioning).

2.3 User Interfaces for Fabrication and Construction

User interfaces (UIs) for industrial robots have hardly made as much progress as UIs in other comparable industries [12]. Thus increasing the ability for non-expert users to interact with a robot was a key motivation for this project, and a key feature which could arguably allow robots to more readily infiltrate the construction industry.

It has already been demonstrated in previous work that well designed human-machine interfaces (HMIs) and background computational coordination have potential for coordinating multiple users in complex building processes; within HMI research just-in-time instructions provided through wearable devices could provide the necessary instructions for non-expert users to engage successfully with robots towards the production and assembly of architecture-scale structures [13].

The advantage of using AR, in addition to screen based interfaces, lies in the ability to overlay digital information over the real-world environment where and when necessary while interacting in real-time using physical and virtual controls. In addition, production statistics and information, assembly sequences as well as machine feedback and control can become more accessible with less training, less preparation time and pre-programming, and also capable of real time updates in response to detected system changes.

State-of-the-art ARHMDs have obvious traits which prohibit their deployment as a universal device for all interface needs, in particular their high cost, short battery life, and limited field-of-view, making it advantageous to develop compatible secondary screen based interfaces.

2.4 AR Applications in the AEC Sector

Several projects have investigated the use of AR in the architectural context. Already in the mid 90´s researcher visualized invisible infrastructure like load bearing columns and their structural analysis using a head worn display [14]. In more recent research, Fazel and Izadi used a head mounted display to guide the manual construction of complex architectural freeform modules [15]. Object interaction and projection-based AR was used to design and robotically transform a seemingly random material system out of melting wax [16]. Newly available plugins developed for computer-aided design (CAD) environments, including Fologram [17], suggest increased opportunities for AR displays as devices which can enable direct three-dimensional feedback superimposed on reality from a digital CAD model.

At the time of submission, limited research has been conducted using AR together with robotic manipulators for the domain of AEC. Fazal and Izadi state in their conclusion that the use of AR can be beneficial for controlling robotic systems [ibid.]. We saw a gap of research where multiple hardware and software technologies could be combined into one system, fabrication workflow, and experience, particularly addressing the need to for robotic interfaces to be compatible with customizable one-off production processes.

3 Methods

3.1 Robotic Workcell and Fabrication Setup

The hardware includes the LBR iiwa robot mounted on a flexFELLOW trolley, a Robotiq 2-finger gripper as an end-effector, a custom-built wood magazine for standard wood stock, a Microsoft HoloLens ARHMD, and a Bosch cordless impact driver for screwing.

The final structure is divided into fabricable building groups called in the context of this research “sub-assemblies”. The fabrication of each sub-assembly takes place on top of an assembly pedestal (Fig. 1). During the exhibition, the robot is moved manually along the pedestal to enable increased reach, though improving robot localization would be a next step in development. Each completed sub-assembly is moved by hand into its predefined position within the final structure, where it is connected to its neighbours with screws.

Figure 1. Robotic workcell and demonstration setup with the assembly pedestal.

3.1.1 Construction System and Computational Process

Though the wooden beams have standardized lengths for simplified implementation in an exhibition setting, the proof-of-concept construction system has the important characteristic of unique rather than standard positions of all the elements, necessitating precise positioning and digital integration. This initial design geometry is generated in CAD software Rhinoceros utilizing a generative design tool and visual scripting language Grasshopper.

Several additional software environments are used for their relative strengths; thus it is critical to establish conventions for interoperability between multiple software environments. To meet this aim, each element in the initial design file and database is given a unique identifier, indicating its assembly number, row and column position.

The driving system principles for the collaborative process are that users execute tasks requiring process knowledge and dexterity, while the robot is used for precise positioning. The HoloLens is deployed as the main HMI and control layer through which this user can plan, dispatch and manipulate robotic path planning in real-time, while also getting live feedback about the current construction status and the state of the robotic system. After selecting a part for fabrication, the path is previewed in the HoloLens. On dispatch, the robot takes an element from the magazine, places it precisely according to the digital model, and then holds the part until the user fasten parts together with screws.

3.1.2 ROS Engine and Communication Network

The core of the system is built using the Robot Operating System (ROS) [18] framework that provides the required communication layer. The ROS server is responsible to manage the CAD geometry, receive and publish robot positions and targets, collect robotic status data, keep track of the fabrication progress, plan robotic paths, and receive commands from the ARHMD and forward them for execution.

The core ROS server achieves this functionality with several features:

- A digital twin of the system that manages system states and real-time environment data
- Path planner based on the ROS package MoveIt! [19]
- Set of ROS nodes that serve as a bridge between the ROS environment and the Java environment of the KUKA Sunrise controller. The bridge nodes are responsible for sending planned actions and receiving real-time robot and gripper data using Google Protocol Buffers (Protobuf).
- Websocket server based on the rosbridge_suite ROS package that provides communication with the components of the system outside of the ROS environment (ARHMD, web-browsers etc.).

Additional important components outside of the ROS framework are:

- MongoDB database for storing the symbolic representation of the CAD geometry.
- Web server that serves as a graphical web interface using the Autodesk Forge Viewer APIs for supervisory visualization of the system data-
- Microsoft HoloLens ARHMD running a user interface build with Unity 3D.
- Rhinoceros+Grasshopper generative design environment able to stream the CAD data in real-time.
- A robot controller running the KUKA Sunrise.OS stack allowing the operation of the KUKA LBR iiwa manipulator.

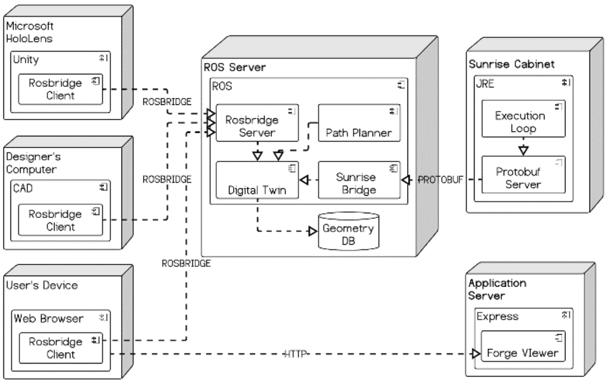

Figure 2. System deployment diagram.

3.1.3 Path Planning

The ROS-based motion planning framework MoveIt! is used for path planning (Fig. 3). Using this framework, it is possible to develop advanced pick-and-place behaviors to be able to precisely position the building elements. These behaviors consider the parameter space of the grasping position of the elements to further enlarge the workspace of the manipulator. By using the current state of the system and its limitations (e.g. arm joint limits) and the known position and shape of the already assembled structure it is possible to plan a collision-free path of the arm. The actual sequence of joint values is calculated using the RRT-Connect [20] single-query algorithm, proving to be a good compromise between the quality of the result and the speed of the calculation for holonomic robotic manipulators with 7DOF.

The "plan" button, selected through the ARHMD, triggers a regeneration and preview of a valid robotic motion. After the user's confirmation, the planned path is sent to the robot controller for execution as a discrete set of joint values.

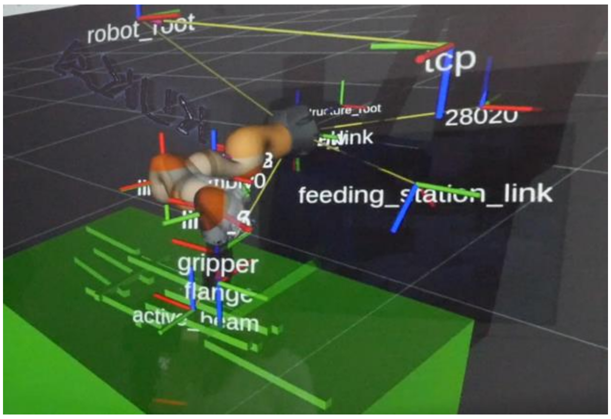

Figure 3. MoveIt! path planning scene with collision meshes visualized with the ROS 3D visualizer Rviz.

3.2 AR Interface

The Microsoft HoloLens ARHMD is used for its built-in stable simultaneous localization and mapping (SLAM) capability as well as for its self-contained nature (i.e. not needing a physical connection to an external device). The Unity 3D game engine is used to develop the AR interface for its integration and compatibility with the Microsoft HoloLens. The interface is kept rudimental and integrates the HoloLens gesture-based input system, by which the user can select and interact with the virtual superimposed content. This feature allows the user to use the UI elements such as virtual toggles and buttons. The robot main actions can be triggered through buttons, labelled as "PLAN" and "EXECUTE", virtually anchored above the selected element that is highlighted yellow (Fig. 4). The "PLAN" button triggers a generation of a robotic path while the "EXECUTE" button triggers the planned movement by uploading a sequence of joint values to the robot controller through the ROS server for execution. If the robot already performs a movement in the time of an upload of a new path the current movement is interrupted, and the newer path is executed instead.

In this UI system diagnostics about the robotic system can also be selectively previewed or overlaid directly on 3D objects including the robot or the production pedestal. The live torques on each axis for example can be displayed.

Lastly a static heads-up display (HUD) is designed in the top part of the AR field of view that displays the more abstract system data and as well as general information such as the overall construction progress percentage or the number of the current sub-assembly.

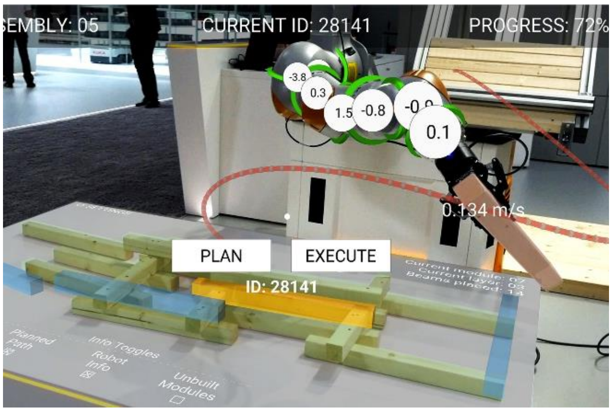

Figure 4. AR view visualizing buttons for selecting, planning, and executing robotic instructions as well as superimposed diagnostic feedback data.

3.2.1 Display Pipeline for Web Visualization

It is well-known that project management is a key component of any complex building process, and multiple concurrent production, finishing, and logistic processes ultimately affect project timelines and need to be considered simultaneously. To provide a scalable solution for unidirectional process supervision, a web user interface is integrated into the overall system communication system. This web interface additionally serves to complement some of the shortcomings of AR, in particular, its higher price and limited battery life are disadvantages which limit the deployment of AR as a universal interface for all needs. The web viewer application was developed using NODE.js and Autodesk Forge Viewer APIs. The application can be executed in any modern web browser and thus it creates a ubiquitous and low-cost solution.

The core of the web application is a geometric scene loaded and displayed in a local web browser client utilizing the Autodesk Forge Viewer API and the WebGL cross-browser JavaScript library three.js. The preloaded scene view already has the robot model as well as the full fabrication model with naming conventions. In this preloaded model, each wooden strut element exists twice, once in its fabrication position and once in its final position. After initialization and loading events, the client browser references a json file that describes what had been already assembled and subsequently updates the scene accordingly. At the same time the browser establishes a TCP/IP communication through the WebSocket protocol to the previously described rosbridge_suite running on the ROS server. The client browser subsequently subscribes to various ROS topics and starts updating the scene. On a successful part place event, the visibility of the geometry in the scene changes from hidden to visible. Any remote user is therefore able to observe the actual fabrication updates and system data in real-time.

4 Results and Discussion

This project and exhibition successfully established a set of tools for facilitating human and robot collaboration in wood construction through enabling AR interfaces. In additional, critical system components in communication protocols were established and verified, including a communication workflow connecting multiple customizable CAD design environments to ROS through common developed data structures. Arguably, one of the core contributions of the project is the achievement of interoperability between multiple software platforms and hardware devices, particularly in the communication between ROS and the Microsoft HoloLens, which had been achieved in precedent projects only in a limited way. The project also demonstrated and achieved a process specific interface for robotic control, and demonstrated increased digital integration by propagating fabrication data downstream into secondary platforms and digital representations.

The advantages of untethered and therefore unrestricted movement and the easy marker less localization setup was extremely advantageous in the environment of a live demonstration on the Hannover fair. The limited battery life of around two hours, plus the reduced computational power of the HoloLens required an extra amount of effort for optimizing the performance which is for a proof of concept project hindrance. Furthermore, the inside-out tracking principle of the HoloLens is based on a spatial mesh mapping of the environment in combination with the data from the on-board inertial measurement unit (IMU). The highly dynamic environment of the ever-changing visitor crowd on the fair was causing an interference in localization resulting in a positional drift that impaired the AR-experience. However, with the rapid development of the AR technologies, these difficulties will arguably be eliminated in future AR-Devices.

While RRT-Connect proved to be a very robust and versatile planning algorithm for the application, its random sample-based nature sometimes resulted in an unsuccessful path when the solution space got smaller. Thus using it in isolation does not circumvent the need to make good kinematic decisions about where the robot should be placed relative to the workbench, to ensure that a viable path will be found. Furthermore, the lack of a well-defined cost function for the robot path proved to be an obstacle for the reproducibility of the robot movements as well as for planning an optimized movement.

4.1 Next Steps

This exhibit was not evaluated by the same metrics by which an interface would be evaluated in the context of HMI research: whereby efficiencies of production workflows with and without the HoloLens could be compared quantitatively. However, it was possible to gain qualitative feedback by visitors who came to the exhibit, predominately users who have extensive experience with programming robots. A next step towards evaluating the usability of the interface would be to test a novice user to interact with a defined objective, where the success of the interface could be measured by whether or not the user could accomplish a predetermined objective without supervision.

The technical implementation could have been improved by more robust localization of the HoloLens: users walking in front the interface was enough for the on-board SLAM to lose its position. A viable option would be the integration of a low frequency external outside-in localization system in parallel that would allow to correct the positional drift or a marker based optical approach that can be additionally used to automatically synchronize the position of the workpiece and the robot arm in a common world coordinate system of the HoloLens.

The presented system also clearly lacked higher cognitive functionality. Simple cognitive cooperation patterns such as joint attention could be highly beneficial in making the HRC scenario more efficient as well as rendering the robot more approachable and lifelike. Without such cognitive features it is hard to imagine that the robot system would become a real co-worker to its human counterpart.

In addition, any of the failures that happened during the course of the exhibition can be attributed to an error in communication, resulting in an incorrect system state, or digital twin model, in one of the environments. These errors could be circumvented by increasing the ability for the human user to enter into the system when an unexpected error occurred. For example, if a part was not loaded in the magazine and was therefore not actually placed.

4.2 Outlook

This project proposed and investigated enabling interactive and interface technologies which can facilitate a more rapid advancement and utilization of robotic fabrication in building prefabrication production chains by increasing accessibility, digital integration, and usability. Simultaneously, the limitations of the project, particularly the limited reach and payload of the KUKA LBR iiwa, point to other technological developments which could accelerate robotic building production processes. In particular, there is a need for collaborative robots designed for the domain of AEC, with specifications including increased reachability, higher payloads, as well as locomotion systems for moving on a difficult terrain.

4.3 Acknowledgements

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