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ABSTRACT

In contemporary digital workflows from design to fabrication in architecture, in which digitally controlled machines perform complex fabrication tasks, all design decisions are typically made before production. However, in such processes, the final shape or form is explicitly inscribed into the design model, and all design decisions are made prior to production. This applies in particular to digital fabrication processes, in which digitally controlled machines require such formal definitions for the execution of fabrication tasks by means of detailed and step-by-step machine instructions (Gramazio, Kohler, and Willmann 2014). While useful for fully automated applications in typical industrial settings, the recent surge in the use of novel augmented reality (AR) technology for digital fabrication workflows requires a more open-ended approach that allows the users to contribute creatively to the fabrication process in any meaningful way.

The purpose of this paper is to develop a formal definition of the final shape as a result of this interaction, the so-called assembly grammar. This approach ultimately leads to the emergence of a final shape and a collaborative workflow. The remainder of the paper is structured as follows. Section 2 outlines the contextual background of prototype-as-artefact fabrication workflows and the current state of the art in this area of research. Section 3 presents the method of the design tool and the fabrication workflow between humans and robots in a shared geometric workspace. It elaborates on the developed assembly grammar and the collaborative building process. This grammar enables, including task distribution strategies between the two users and the robot. In Section 4, the results of the case study of the complex timber structure- enabled by the developed workflows and interaction concepts are described. Section 5 presents the conclusions and gives a future outlook of this research. In closing, the paper discusses if such a balanced integration of robotic fabrication processes in coordination with humans could open up new avenues for design and digital fabrication in architecture.

INTRODUCTION

In contemporary digital workflows from design to fabrication in architecture, the final shape is explicitly inscribed into the design model, and all design decisions are made prior to production. This applies in particular to digital fabrication processes, in which digitally controlled machines require such formal definitions for the execution of tasks by means of detailed and step-by-step machine instructions (Gramazio, Kohler, and Willmann 2014). While useful for fully automated applications in typical industrial settings, the recent surge in the use of novel augmented reality (AR) technology for digital fabrication workflows requires a more open-ended approach that allows the users to contribute creatively to the fabrication process in any meaningful way.

The purpose of this paper is to develop a formal definition of the final shape as a result of this interaction, the so-called assembly grammar. This approach ultimately leads to the emergence of a final shape and a collaborative workflow. The remainder of the paper is structured as follows. Section 2 outlines the contextual background of prototype-as-artefact fabrication workflows and the current state of the art in this area of research. Section 3 presents the method of the design tool and the fabrication workflow between humans and robots in a shared geometric workspace. It elaborates on the developed assembly grammar and the collaborative building process. This grammar enables, including task distribution strategies between the two users and the robot. In Section 4, the results of the case study of the complex timber structure enabled by the developed workflows and interaction concepts are described. Section 5 presents the conclusions and gives a future outlook of this research. In closing, the paper discusses if such a balanced integration of robotic fabrication processes in coordination with humans could open up new avenues for design and digital fabrication in architecture.

CONCEPT

Towards Non-Linear Digital Design to Fabrication Workflows

The computational theory of making grammars, presented by Knight and Stiny in 2015, has extended the theory of shape grammars for the study and the digital representation of the temporal performance of craft in contrast to representing solely the product (Knight and Stiny 2015), ultimately aiming at replacing top-down design thinking by bottom-up material processes of formation (Ingold 2010). By understanding the act of making in craft “as doing and sensing with stuff to make things”, they described its underlying creative processes by segmenting their spatial and temporal properties of applying rules for both actions of making and sensory perception. Such processes are open and do not fully determine the outcome in advance. They allow practitioners and users to change plans on-the-fly, for example, to pursue new design ideas that are triggered by the pattern in progress, or to accommodate for mistakes (Knight 2017). Also, in Sennett’s observations on Ruskin’s worldview (Sennett 2008), he advocates for craft processes as “lost spaces of freedom”, in which craftspersons experiment with ideas and techniques, risk mistakes and delays, and “can at least temporarily lose control”. In the context of contemporary industrialized production, the early Enlightenment
A machine ought to propose rather than command, and while the final configuration of the spatial timber assembly final geometric result is not explicitly determined before fabrication, computation strategies are used to inform the user about possible design spaces and the feasibility to integrate physical boundary conditions of material structure. Rather than competing against the machine, exploring the relationship between rationalized industrial production techniques and traditional craft could show us entirely new ways in which we make and build architecture.

Our proposed geometric aggregation strategy therefore aims to connect the bottom-up generative engineering with computational methods in design and fabrication. While the final configuration of the spatial timber assembly is unplanned, the process of assembly is governed by a simple rule-based geometric process (described in Section 3) in combination with human decision making and physical constraints. As such, this strategy aims to integrate physical boundary conditions of material processes in architecture (robotic reach) into the open-ended fabrication processes in architecture via different direct and indirect user input technologies that have been demonstrated in recent years. For example, Interactive Fabrication shows how a user can direct the fabrication of a physical form by using real-time user input (Mueller et al. 2019). In Interlacing, camera tracking allows for the 2D observation of a robot workspace, enabling a robot to process various material inputs and to make design decisions within a constrained design space during fabrication (Dörfler, Rist, and Rust 2012). In RoMa, an interactive fabrication system provides an in-situ modeling experience for users (Peng et al. 2018). As a designer, creates and adapts a model using the RoMA CAD editor in AR, a 3D printing robotic arm sharing the same design space, volume concurrently constructs the designed features. In FormFab, Continuous Interactive Fabrication, the interactive manipulation of a thermoplastic sheet allows for shape explorations directly in the physical space (Mueller et al. 2019).

While novel technology and approaches have allowed for a major leap forward in this area of research, the demonstrated strategies to date still show various trade-offs. For example, few investigations have been performed on how to utilize user input as a feedback to the computational design engine directly via the built structure. While the input of sensors is defining the robot actions for manipulating an object in Interactive Fabrication, RoMa, and FormFab, the physical result of the robotic manipulation procedure is not registered and is therefore not directly part of an interactive loop. While Interlacing aimed to provide such feedback directly via the built structure, it was highly constrained by lacking an adequate sensor and 3D registration technology and intuitive human-machine interfaces. Most importantly, all described processes have been performed at object scale and have not tested and evaluated the principles of interactive fabrication at the architectural scale and in the context of architectural production.

In Prototype As Artefact, the user input is processed directly via the built structure by tracking elements which are placed spontaneously by users and by feeding this information back to the digital model. This approach allows for an interactive and collaborative workflow between humans and robots at architectural scale.

METHOD
The aim of the research was to develop a set of workflows and technologies to facilitate an interactive human-robot collaborative workflow for assembly tasks, with a particular consideration for the unique needs and circumstances of architecture and construction. The following sections describe the various building blocks and implemented methods necessary for realizing this research project.

Assembly Grammar
In reference to Terry Knight’s Making Grammar, this research proposes an Assembly Grammar, which allows for the description of rules for temporal processes next to geometrical ones. The design rules of the proposed assembly grammar allow for building spatial structures by mechanically connecting discrete elements in subsequent fashion. In the digital model, referred to as the Assembly Information Model, each element is represented by a node of a graph; the edges of the graph correspond to the connections between the elements. Each element features two connectors on both endings on the long side of the element, which corresponds to two anchors in the digital graph. The initial design rule (Fig. 2) that directly affects the geometrical outcome is described by the geometrical configuration of three perpendicular elements into a module with a predefined range of connection possibilities. Due to the module’s perpendicular spatial arrangement, each element has a different type assigned to it – each module consists of one element of type X, one of type Y and one of type Z. These also refer to the orientation of the elements along a respective axis in the digital design model (Fig. 2). The connection between two modules (but not the connection between elements within a single module) is represented as a parent-child connection, in which the module that is already mounted is referred to as the parent and the newly mounted one as its child. The first element of the child module inherits the type of its parent: parent type X → child type X’ Y’ Z’ = X’, Y’ Y = Y and Z’ Z = Z. The type of the parent module’s first element and correspondingly of its child determines the type and sequence of the placement and mounting of the subsequent two elements. Depending on the type of the parent, the sequence can have the following order: if the parent is of type X, the mounting sequence is [X, Y, Z]; if the parent is of type Y, its sequences are [Y, X, Z]; if the parent is of type Z, its sequences is [Z, X, Y]. There exist a few exceptions to these rules, for example, the mounting sequence for
The screws are inserted through the holes of the pre-drilled element that is to be attached to the structure and screwed in the desired member of the structure with a portable electric screwdriver. By inserting two rather than only one screw at the lap joint sufficient stiffness of the connection has been reached. The screw connection also enables an easy disassembly of the structure and reuse of both timber and screws.

Collaborative Human-Robot Assembly Setup

The setup of the proposed collaborative workflow for assembling the timber structure in alternating physical actions consists of two users, which are equipped with a mobile AR device and complemented by a semi-mobile collaborative robot (Fig. 6). The mobile AR device enables both the users and the robot to build on the same workpiece, which is enabled by two key features: 1) The visual display of the AR device can superimpose cues on the real-world video stream designed to assist the builders with information, in this particular case with visual cues on the design space in which they can make their design choices; this is achieved by tracking and registering the user and machine actions of assembling timber elements into the spatial structure, in which each spontaneous user action is followed by a robot action. The combination of the timber elements into modules of three thereby represents the alternating assembly sequence between the user (keystone element, freely placed by hand) and the robot (second and third element, computed and placed by the robot).

One iteration starts with the user tracking the built structure and observing the design space visualized via the AR interface (Fig. 7). The design space is visualized in the representation of arrows superimposed on the built timber structure, in which the arrows indicate the open connectors and possible directions where the structure can continue to be built and branched out. The location of the arrows are subject to various boundary conditions, in this case, the definition of initial target locations to where the structure should grow towards, as well as the current robot workspace. The user can then choose any location within the current given design space to place the keystone element (Fig. 8a), while the chosen connection is then fixed in angle, the distance along the parent element’s axis is subject to the user’s decision. After having the element placed and mechanically fixed, its precise location (position and orientation) is then registered by the user via the AR device (Fig. 8b) and fed back to the design engine (Fig. 8c).

In response to the user’s freely placed element, the design engine then computes the location of the two subsequent elements to complement the module by sequentially placing the two computed elements, their corresponding robotic pick-and-place routines need to be calculated. The planning scene creation and the motion planning are done through COMPAS Fab, the robotic fabrication package for the COMPAS Framework (Sandy et al., 2018), by using the Mavros Package from the Robot Operating System (ROS) backend. In the closing of one iteration, the two elements are placed according to the computed robot motions (8e).

Interoperability and Cross-Platform Communication

To ensure the interoperability between the multiple devices and back-end computational processes for the collaborative assembly process, a necessary component is a scalable middleware technology as the communication infrastructure for the distributed system. In this case, this was achieved by using ROS, which is currently the state-of-the-art in robot middleware, providing a scalable socket-based programmatic access to robot interfaces and algorithms, that external processes can access through the robridge package and roslibpy of COMPAS Fab. Here, the ROS system architecture is utilized to connect the multiple instances of a) the design computation process embedded
To test the developed workflow and toolsets, a case study was conducted, whereby two users and one Universal Robot (UR10e) collaborative robot interactively constructed a medium-scale architectural prototype. The prototype was realized on a building floor area of 2 x 3 m consisting of 6 MDF boards with dimensions of 1 x 1 m each and 6 mm thickness. This MDF flooring served both as a base for mounting the prototype with the elements placed on the ground to it and as a neutral background for the tracking. Additionally, dark light proof and non-reflective fabric was suspended around the building area to exclude unnecessary surface edges from the tracking scene. To provide constant lighting conditions and thus uniform tracking results, only artificial light was used over the entire building process. A free space described by a rail of 120 cm between the base of the prototype and the black coverings was used for the robot to be moved around within, as well as to allow for enough space for the robot motions.

A total of 102 timber elements were installed over the course of three days (Fig. 9), of which 16 were freely placed and tracked by a user, 56 were placed by the robot from three different locations, and 30 were placed by a user which could have been placed by the robot but were placed manually instead. This manual placement was also made possible via the app, as the elements calculated by the design algorithm were visualized and the user could follow the superimposed outlines of the digital model over the real video stream while placing them. At each of the three robot’s locations, the robot’s origin was determined by matching manually recorded corner points of the built structure with the robot’s measurement tip with their point location in the digital model. The tracking accuracy was observed to be well between 3 mm as indicated by ground truth measurements with the robot’s measurement tip. The color gradients in the error plot (Fig. 10) indicate the deviation in distance (red) and rotation (blue) from the estimated object poses to the poses of the planned elements which follow a rectilinear grid as defined by the design algorithm.

RESULTS

To follow the superimposed outlines of the digital model over the ground to it and as a neutral background for the tracking, and implicit human knowledge and creativity. The realization of this concept was facilitated by state-of-the-art object tracking technology of an AR app, which provided the facility to register single objects precisely in 3D space and in relation to the built structure. The concepts and methods have been successfully evaluated and validated on behalf of one case study, the collaborative assembly of a branching spatial timber structure.

In this study, the global growth directions and local branching rules of the structure to be constructed were defined by the users at the start of the process. During the process, the users could follow the suggested directions that were visualized to them via the AR app, but make individual and spontaneous decisions within these suggested options. As such, the process facilitated the creative participation of humans in a digital building process by integrating creative decisions during the ongoing process. Design computation in this case was utilized not only to calculate a finished structure ready to be fabricated, but to continually calculate a potential design space and according building options based on the users’ decisions/input, as well as its corresponding robotic fabrication procedures. The result of this project was a timber structure—a complex 3D branching structure with varying densities—sequentially designed and built collaboratively on the basis of the user’s design input and physical boundary conditions. In summary, the project has made it possible to question typical roles of designers, builders and robots. Transferred to practical applications for the architecture, construction, and engineering industry, the proposed workflow also lays the foundation for future scenarios, implementing advanced technologies on the construction site, in which builders could actively intervene, physically or cognitively, supporting or steering automated processes towards higher levels of robustness and efficiency in complex or unforeseen scenarios.

CONCLUSION AND OUTLOOK

Conclusion

The research presented in this paper has explored a novel open-ended digital fabrication workflow by introducing non-linear design-to-fabrication processes. On the basis of an implemented design tool for the sensible distribution of tasks between humans and robots, this novel workflow could be carried out by two users and a collaborative robot. They all worked together in designing and assembling an unplanned spatial structure, combining explicit machine intelligence and implicit human knowledge and creativity. The realization of this concept was facilitated by state-of-the-art object tracking technology of an AR app, which provided the facility to register single objects precisely in 3D space and in relation to the built structure. The concepts and methods have been successfully evaluated and validated on behalf of one case study, the collaborative assembly of a branching spatial timber structure.

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Outlook

While this research has allowed to demonstrate the core concept of non-linear and open-ended digital design-to-fabrication workflows, many directions for future work have been identified:

Structural evaluation: While structural evaluation is usually important for the final shape, in this research, maintaining structural stability during production is of great importance in order to ensure its equilibrium without further support. Due to the number of built elements compared to the scale of the built prototype, its structural behaviour could be intuitively anticipated by the users and thus affect their design decisions during building. This reduced...
This paper and the research were supported by incon.ai who

ACKNOWLEDGEMENTS

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Lidia Atanasova is an architect and Ph.D. researcher at the TT Professurship Digital Fabrication (Augmented Fabrication Lab) at the Faculty of Architecture and associated with the Faculty of Civil, Geo and Environmental Engineering at TU Munich.

Daniela Mitterberger is an architect and a Ph.D. researcher and A&T Ph.D. Fellow at the Chair of Architecture and Digital Fabrication (Gramazio Kohler Research) at ETH Zurich. Daniela is also the Co-founder and Director of MAED – FutureRetrospectiveNarrative, a multidisciplinary architecture practice based in Vienna.

Timothy Sandy received his PhD in robotics, as a part of the NCCR Digital Fabrication at ETH Zurich in 2018. In 2020, he was awarded an ETH Pioneer Fellowship and is building the spinoff incon.ai to provide augmented reality guidance tools to fabricators and construction workers.

Fabio Gramazio is an architect and co-founder of Gramazio Kohler Research, an architectural robotics laboratory at ETH Zurich. Gramazio Kohler Research has been formative in the field of digital architecture, creating a new research field merging advanced architectural design and additive fabrication processes through the customised use of industrial robots.

Matthias Kohler is an architect and co-founder of Gramazio Kohler Research, an architectural robotics laboratory at ETH Zurich. Gramazio Kohler Research has been formative in the field of digital architecture, creating a new research field merging advanced architectural design and additive fabrication processes through the customised use of industrial robots.

Kathrin Döfler is leading the TT Professurship Digital Fabrication (Augmented Fabrication Lab) at the Faculty of Architecture and the Faculty of Civil, Geo and Environmental Engineering at TU Munich. Research in the Augmented Fabrication Lab is dedicated to fabrication-aware design and robotic fabrication processes.