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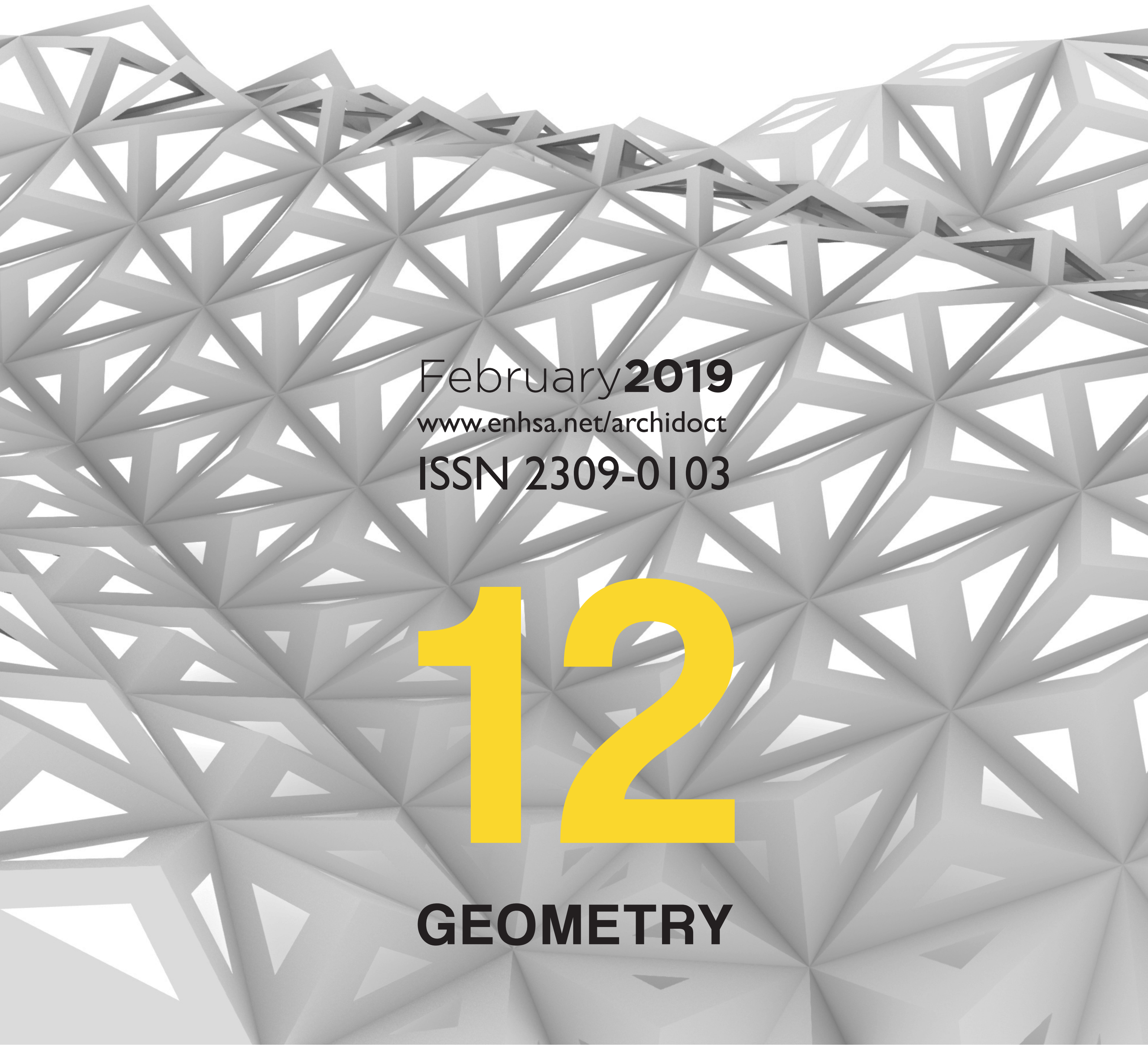

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## GEOMETRY

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# Using Materially Computed Geometry in a Man-Machine Collaborative Environment

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## Abstract

*In this research, we interweaved real-world geometry with computational tools for a man-machine collaborative assembly process. Current research for robotics in architecture aims to bridge the gap between digital design and fabrication, but rarely considers manipulation of real-world geometry by human actors. In contrast, we utilized material computed geometry as a physical interface. 3D scanned wooden lamellas served as input for computational tools to finalize a design and create toolpaths for the robotic placement of rods.The research combines methods of machine vision, physical interfaces and man-machine collaboration to restructure workflows in the process of design and construction. Consequently, real-world geometry was used as input to start the design process. The designer engaged with wooden lamellas and a computational tool to build a demonstrator, illustrating a clear division of tasks in a man-machine collaboration. Moving from parametric design tools directly to physical interfaces using real-world geometry, our research proposes a stronger participation of human actors within digital fabrication environments.*



## Keywords

Construction/Robotics; Machine Vision; Man-Machine-Collaboration; Real-World Geometry; Physical Interface

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## 1. Introduction

In this article, we present a physical design interface that uses manipulated wooden lamellas as an input for a man-machine collaborative process. The significant contributions of the work are:

- A physical design interface as part of a built structure
- Real-world geometries that serve as input for an algorithm, which automatically creates data for robotic fabrication
- A collaborative man-machine building process that is augmented using projection mapping

Architecture research in robotics creates a link between digital data and the material world and allows for new concepts of materialization. Moreover, these orchestrated systems show a high degree of automation that allow for thousands of repetitions of a similar yet variable task without human interference.

In contrast to most research, we focus on the question of how humans can collaborate within digital robotic construction processes through real-world geometries. Therefore, we develop a user interface with a 3D scanning device to merge the real-world into the digital. Questioning the clear separation of the two worlds, we demonstrate how they can inform each other.
Certainly, the division of tasks between users and robots will become more relevant due to growing advancements of autonomous robotic operations in architecture.

This paper is divided into four parts. The first explains the framework and background of this research by naming the main fields of interest: material systems, physical interfaces, machine vision, and man-machine collaboration. The second part describes the method with all its relevant parts that were used to build a demonstrator, which illustrates the proposed framework. In the third part, we evaluate our findings on physical interfaces, machine perception, and man-machine collaboration and explain challenges within such a framework. Finally, we review the contribution that material-based modeling environments can make in architecture through man-machine collaboration and offer some suggestions for future research to implement our proposed framework.

This research explores if real-world geometry - as physical interfaces for a man-machine collaborative process - can be part of a built structure to challenge the common division of planning and construction.

## 2. Background

In order to begin defining novel architectural production strategies that can integrate user intentions and robotic fabrication strategies, it is necessary to bridge a series of related research fields. We reviewed physical interfaces, machine vision and man-machine collaboration to create a foundation for the presented research.

*2.1 Geometry Computed by Material*

Material properties and their integration into design systems and construction processes have been researched within the last decades. Frei Otto showed how analog large-scale models were used for form-finding. Although digital simulation techniques already existed in 1975 for anticlastic surfaces, they were in their early stages. Hence their design interface and the geometrical representations were relatively basic. Thus, as structural properties are scalable, models served as design interfac-

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es by taking measurements manually or via precision cameras and photogrammetry (Otto et al., 1975). Overall, those models are geometric representations of physical form-finding processes for a specific material system.

Materials have the capacity to compute and thus inform the design process with their physical properties. (Menges, 2012). Here the question is how to combine the advantages of both the digital and material computation. Cyber-physical systems combine digital computational logic with the dynamics and uncertainties of the physical world through actuators and sensors (Rajkumar et al., 2010). Recent research on robotic systems in architecture shows possible real-time actualization of production data. Based on the feedback of the measurements, the error margin encountered within the fabrication is reduced. This consequently forms a stronger connection between the digital model and material system.

Our research looks at how a material system can be informed through human interaction with real-world-geometry.

*2.2 Physical Interfaces*

The conventional design interface to generate geometry in architecture is the computer. In contrast, we propose using real-world geometries as tangible user interfaces that stay part of the built structure.

Thus far, several studies have shown that tangible user interfaces allow the change of physical objects as an input device for design tasks (Herr et al., 2011); Balakrishnan et al., 1999; Grossman, Balakrishnan and Singh, 2003). Moreover, augmented physical interfaces offer the possibility to project digital information onto an existing structure to visualize properties like load failing probabilities or stress distribution (Savov, Tessmann and Nielsen, 2016; Johns, Kilian and Foley, 2014).

*2.3 Machine Vision*

Machine vision frames the field that enables machines to extract visual features of the real world. In the building industry, machine vision is used to create as-built Building Information Models (BIM) using 3D point clouds captured via laser scanners from the construction site. Many studies have demonstrated that scan-to-BIM is a sufficient way of comparing the actual building with the planned model (Macher, Landes and Grussenmeyer, 2017). So far, little attention has been paid to integrating object recognition for manipulated components and to merge them back into the digital design model.

In robotic construction research, one commonly used sensor is the Microsoft Kinect depth sensor that allows visual feedback in the form of 3D point clouds from built structures (Brugnaro et al., 2016). Moreover, Bard has shown that machine vision can be used to embed real-world objects or human gestures into human-robot collaboration processes. Physical making and generative computer models simultaneously inform design processes through those hybrid workflows (Bard et al., 2014).

However, the implementations in architectural production are still limited due to insufficient computational tools to interpret or segment the data from visual sensors. We are aiming to extract geometric features according to their relevance for design tasks.

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*2.4 Man-Machine Collaboration*

Task-shaping is an emerging research area in the field of robotic fabrication in architecture. As an aspect of man-machine interaction, it describes how new technology, like robotics, effects the way human tasks change within an automated fabrication environment (Goodrich and Schultz, 2007). A clear division of tasks and skills is delineated by several researches in the field of robotics fabrication in architecture (Nguyen et al., 2016; Helm, 2014). Moreover new process chains indicate a stronger connection between physical and digital construction systems, allowing users to interact and command during robotic assembly processes (Rossi & Tessmann, 2017). Likewise, human gestures can link the human body with the digital fabrication environment (Johns, 2013). Our research seeks to identify a division of tasks that highlight robotic qualities in a collaborative assembly process.

## 3. Method

Man-machine collaboration in design and construction processes is a rapidly growing field, as robotics bridge the gap between the physical and digital world. We explored modes of collaboration through a demonstrator made from bendable lamellas, fixated by wooden rods, that yields its temporary configuration through a process that coalesces design and construction into a fluid process of man-machine interaction (Figure 1).

We sought to identify the most effective way to share tasks among all parties involved to benefit from the abilities of both humans and machines. While robots effortlessly position elements in planes in space regardless of inclination and orientation, humans can coordinate complex assembly sequences through senses, experiences, and intuition (Figure 2). Finally, computational design software generates large numbers of gradually diversified building elements. These different capabilities were exploited in our research through the following steps:

We built a demonstrator based on the notion of a material system (Menges, 2012) that acts as an input for the computational design tool that is actuated by human shaping and robotic vision via 3d scanning (18 wood lamellas, Kinect 2, Grasshopper, Firefly).

We implemented a way to extract specific features of a 3d point cloud that serves as an input for an algorithmic design tool (Grasshopper, Volvox).

We developed a collaborative placement process of wooden lamellas for humans and robots, with a clear separation of tasks. Its features are visual guidance for humans through projection, precise placement of rods and a friction based assembly method.

The process began with the manual design and placement of two wooden lamellas at the left and right edge of the foam board (Figure 3). Their curvatures, inclinations, and shape were designed through direct engagement with the physical object (Figure 4). The designers negotiated forces, design intention, and material behavior into one geometrical configuration while avoiding breaking the lamellas. The desired shape was fixed by wooden rods punched into the foam board.

The 3d depth sensor (Microsoft Kinect 2) was mounted to the six-axis robot (UR10, Universal Robots) to fully scan the physical set up. Based on the robot's position the point clouds were combined into one digital model (Figure 5).

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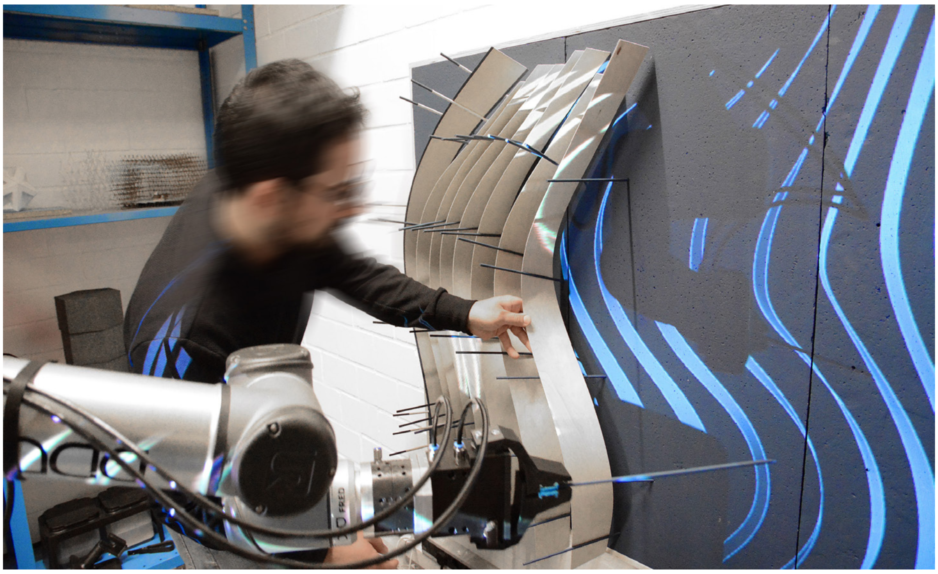

**Figure 1.**
The demonstrator for the man machine collaboration illustrates a division of construction tasks.

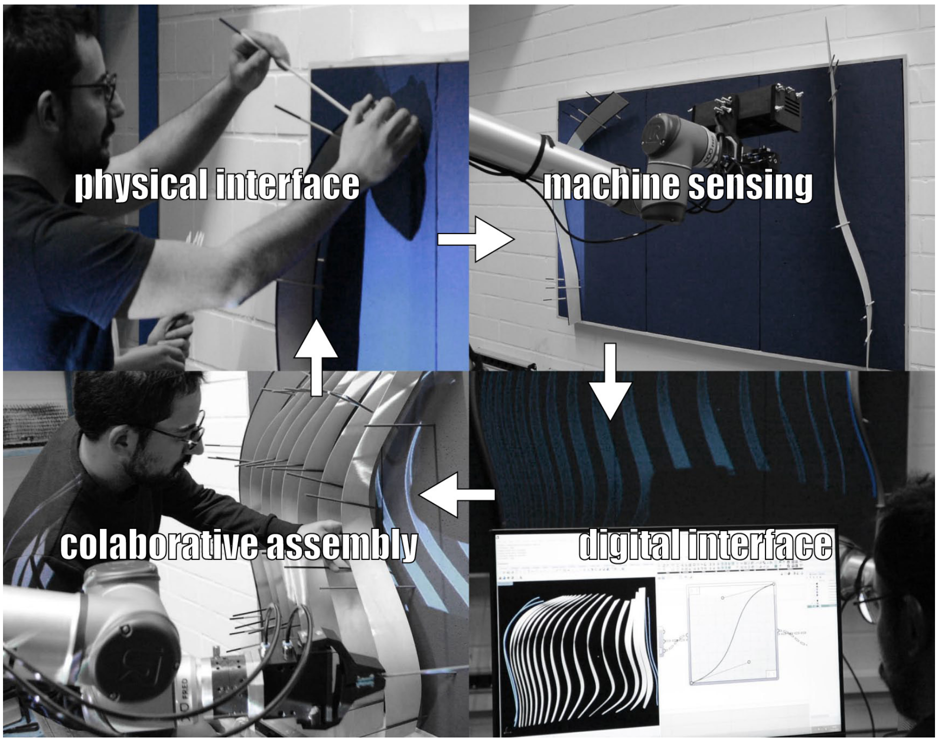


**Figure 2.**
The research links physical design, machine vision, computational design and man-machine fabrication.

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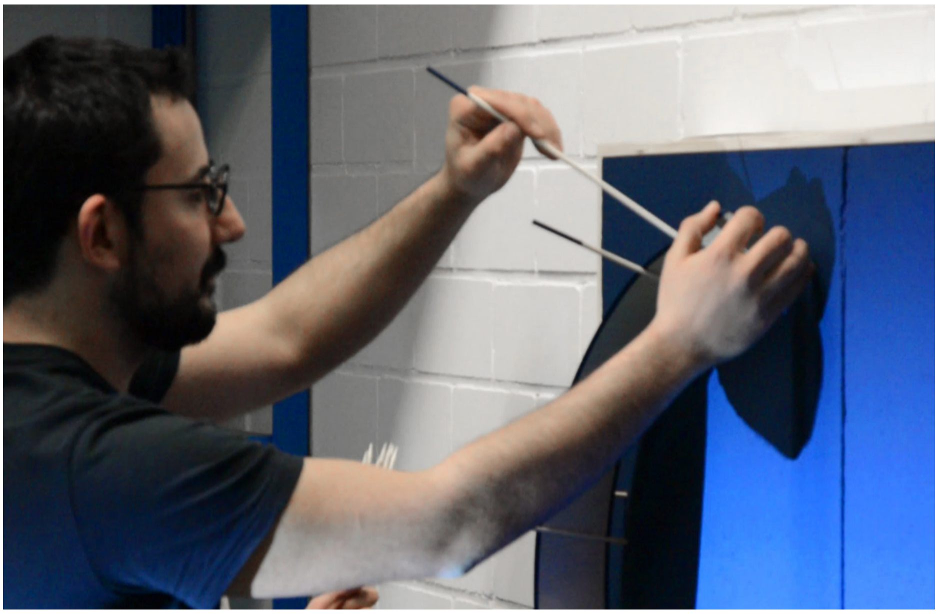

**Figure 3.**
The designer shaping the input lamellas and placing rods for their fixation.

**Figure 4.**
Lamellas placed.

**Figure 5.**
Robot arm with mounted Kinect 2 scanning the input lamellas from different positions.

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The point clouds were processed and separated for each lamella using the Volvox plugin for Grasshopper. A Grasshopper script extracted the design features from the point clouds. A mesh is generated from the point clouds, and the top and bottom edge of the lamellas were computed as curves, and represented in the digital model (Figure 6). The extracted curves served as input for the parametric design algorithm. Showing the advantage of digital computation, we implemented an interpolation strategy to create differentiated geometries based on the inputs. The extracted features were interpreted by the algorithm to construct a series of lamellas. The distance between the top edges and bottom edges of the input lamellas was measured and equally divided to draw the digital lamellas. Graph mappers integrated into the interpolation design tool allowed the user to control the positioning, orientation and rotation of the interpolated lamellas through a numerical differentiation based on visual input (Figure 7).

The lamellas follow the definition of ruled geometries. As such, they can be described through a series of straight lines, which are called generators (Figure 8) (Pottmann et al., 2007). Already, the physical input lamellas follow this logic through the placed rods. For the robotic construction, the rod positions, directions, and associated planes were extracted from the digital lamella model based on the surfaces generators (Figure 9). Those were simulated with the Grasshopper-Plugin Robots and then sent to the robot for precise arrangement (Figure 10).

The assembly process was divided into the positioning of the rods and the lamellas. The rods require a precise placement as their position and orientation controls the bending of the lamellas, which was achieved by the use of the six-axis robot. The lamellas friction based assembly logic calls for a more complex process sequence; therefore this part is done by humans, based on vision and touch. The assembly is supported by a projection mapping of the digital model onto the physical, and serves as guidance during the manual assembly of the lamella distribution between the rods.

The material system of rods, lamellas, foam board, and robot allows for a reconfiguration of the model. Therefore, the whole model is scanned, and the actual position of the rods is extracted from the point cloud. The design algorithm can be fed with new inputs generating a new lamella configuration. The physical and digital configurations are compared by measuring the distance between the physical and digital rod positions. The comparison results flow back into the previously described process. While there are no new lamellas added the robot pulls out existing rods from the foam board and places them in new positions. The lamellas stay within the model during the process and are transformed by the robotically moved rods.

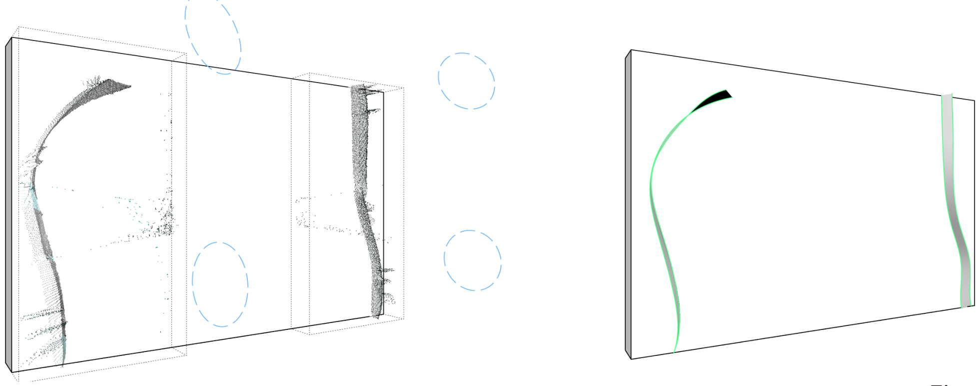

**Figure 6.**
The dashed circles represent the scanning positions of the robot. The lamellas edges are extracted from the point clouds.

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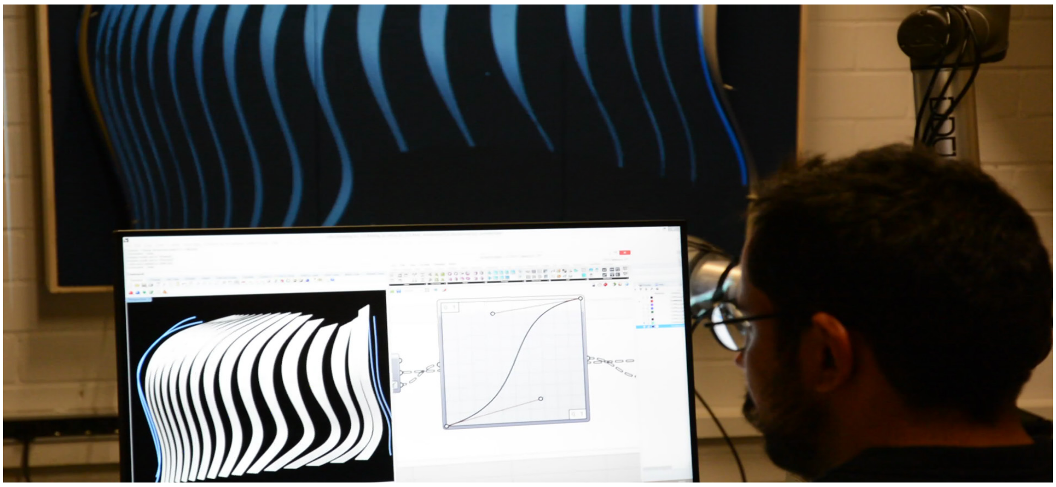

**Figure 7.**
Design tool interpolating the lamella positions.

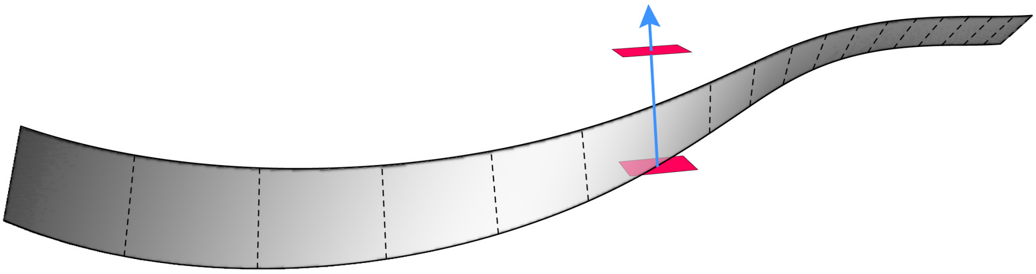

**Figure 8.**
Ruled surface with its generators as dashed lines and two planes extracted from the generators vector for the robotic path planning.

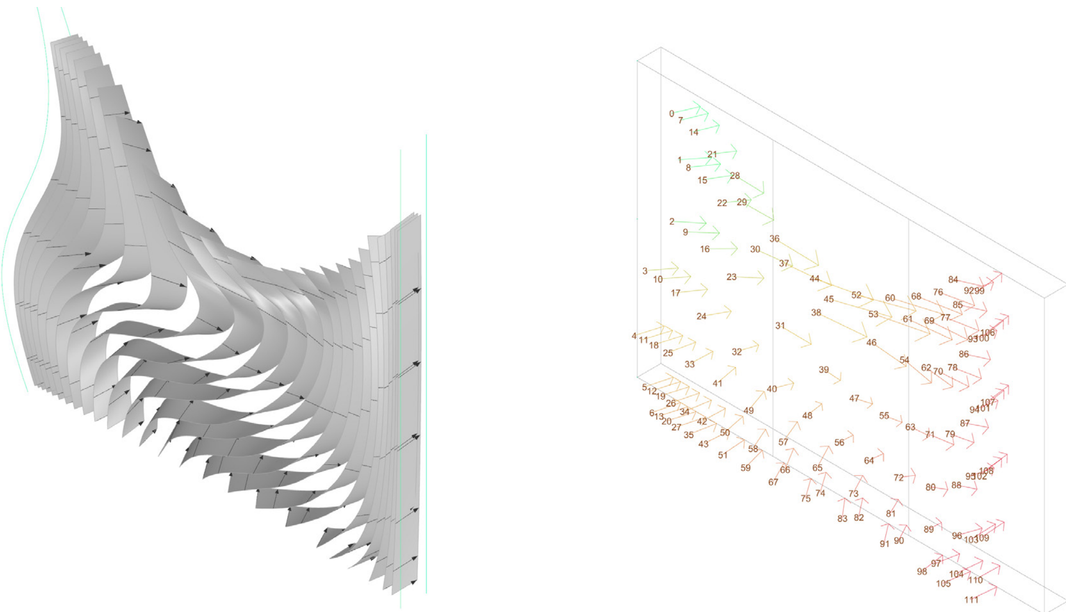

**Figure 9.**
Planes and Vectors for the robotic process extracted from the digital surface model.

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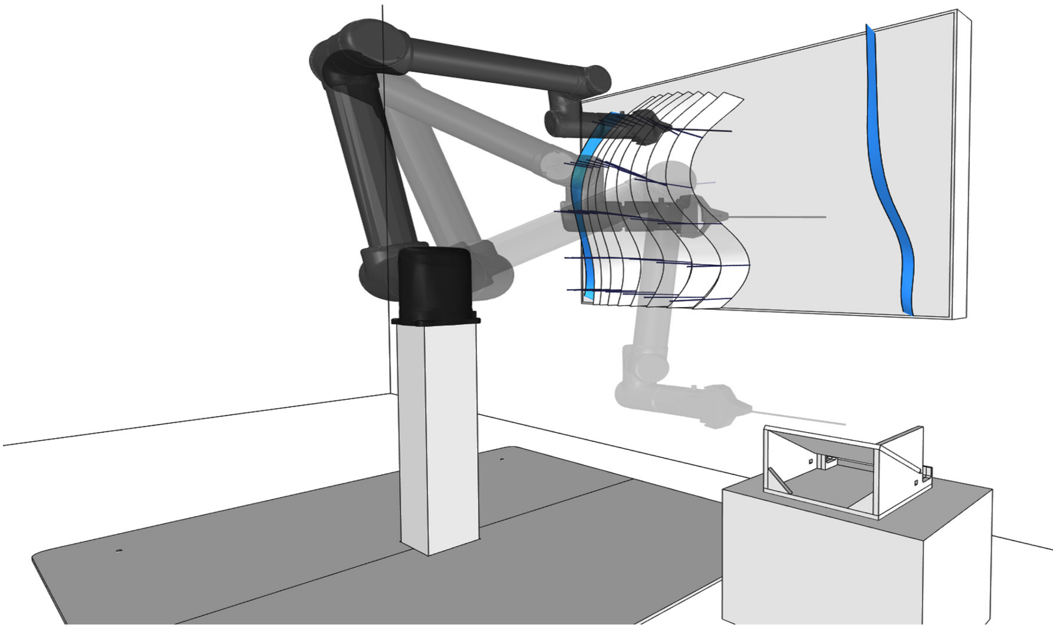

**Figure 10.**
Simulation of the robot paths with the main tasks: pick-up, positioning and placement.

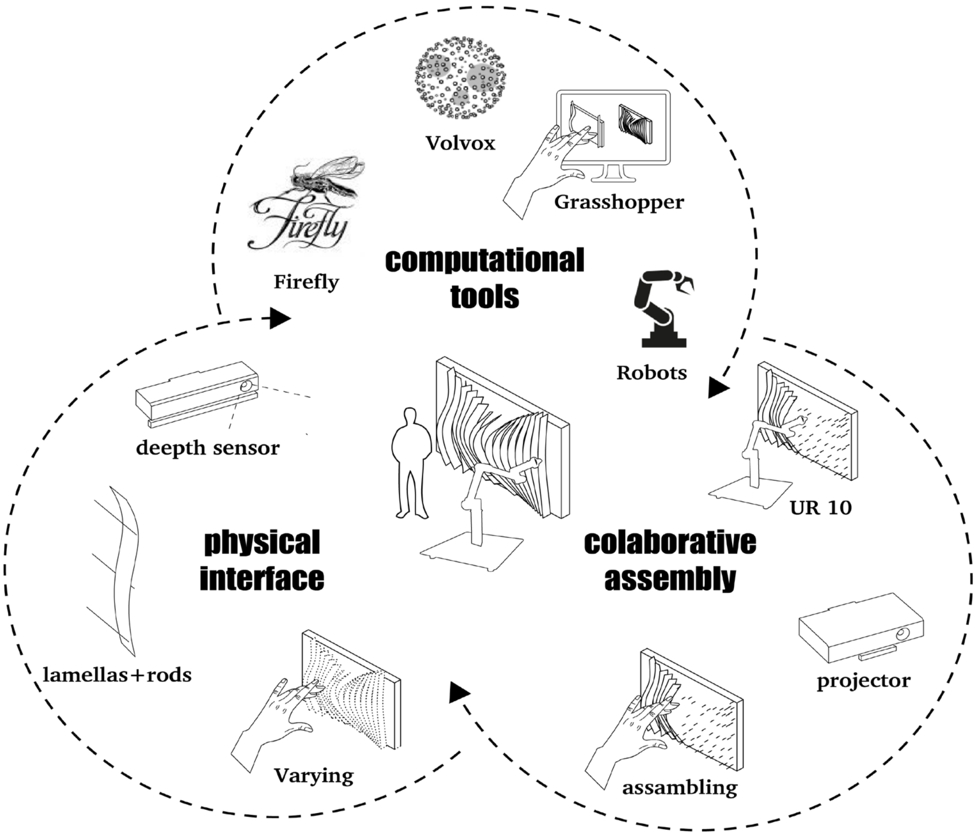


**Figure 11.**
Human represented by a hand within the process.

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## 4. Results

The project challenges the sequence and tool use of conventional design to production workflows and carefully intertwines human design interventions with machine vision for a robotic construction process. Moreover, it uses a physical interface within the architectural process of design and construction to generate materially computed geometries (Figure 11).

*Material Interface*

The material properties and constraints of the wooden lamellas gave rise to a certain geometric configuration. The placement of the lamellas served as input for the parametric design tool. This interface was used to enable users to interact with real-world geometries while taking into account material properties and constraints like bending behavior and friction between rods and lamellas. Moreover, users without prior knowledge of the design interface were able to configure lamella designs sufficiently.

*Digitalization of Design Intend*

The 3d scanning was precise enough to generate the necessary data for the digital representation of the manually shaped lamellas. The captured point clouds had a maximum distance between the points of 2mm. The density was high enough to create meshes from which the edges of the lamellas were extracted. The used plugin Firefly for Grasshopper caused minor problems, showing unnecessary points that were assumed to be a result of the plugins interpolation algorithms between infrared depth sensor data and image data. Those points were avoided by a coloring the edges of the lamellas which allowed to cull the points by color. Subsequently, the physical set up was 3d scanned and translated into a digital geometry.

*Computational Differentiation*

The computational design tool used the input curves from the physical lamellas for its interpolation algorithm. The operator of the algorithm interpolated 16 lamellas between the input lamellas. The material constraints were embedded in the parametric design tool through the scanned geometries set by the operator. The final design was found after several iterations of tweaking the design parameters. The goal for the design was to achieve an appropriate differentiation of the inclination and distribution for the lamellas. From this digital surface model, the rod positions and inclinations were extracted as vectors to fix and hold the lamellas and generate the robot tool paths.

*Collaborative Process*

The collaborative construction process took 45 minutes. The projection enabled for the correct placement and alignment of the rods (Figure 12). Manual placement of the lamellas was synchronous with the robotic rods placement (Figure 13). The robotic rods placement illustrated the high precision of the six-axis robot and the digital model. The reconfiguration of the demonstrator was tested in a smaller model (Figure 14). Rods were identified using visual sensing capabilities. The repositioning of rods with lamellas in place needs to take into account the constraint of the lamellas bending behavior.

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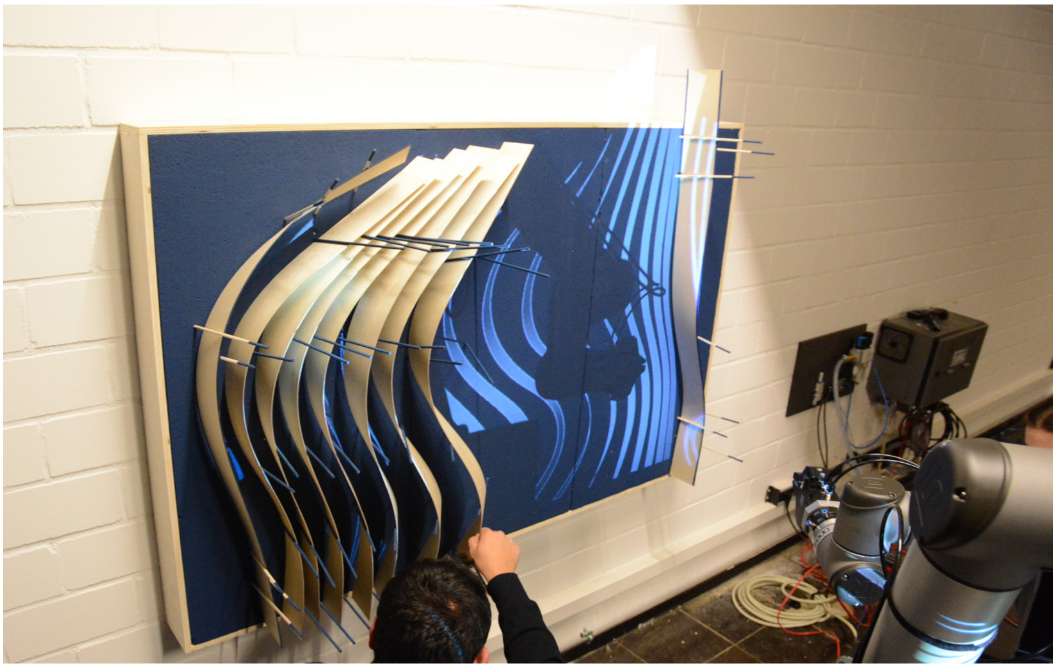

**Figure 12.**
Projection guiding the human during the collaborative assembly process.

**Figure 13.**
Projection of lamella alignment and curvatures

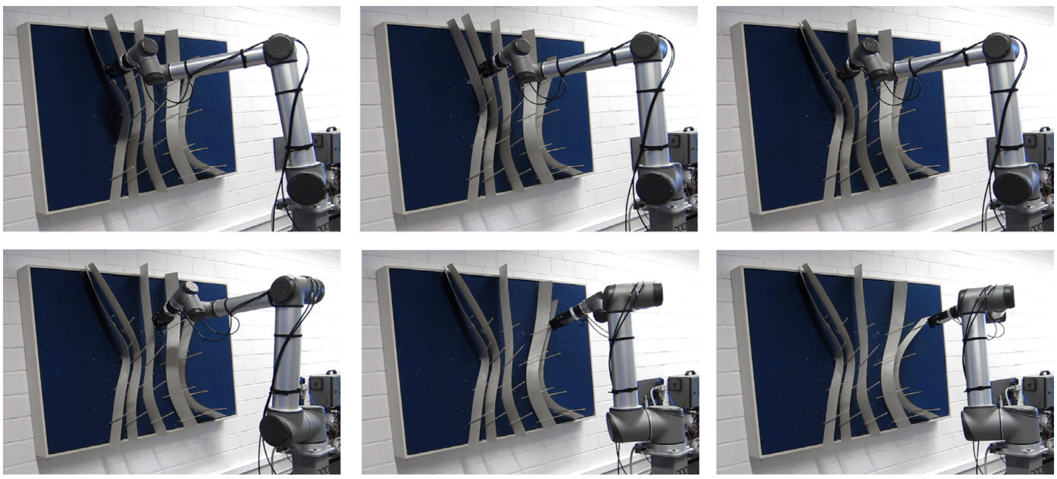

**Figure 14.**
Robot changing the position and orientation of lamellas.

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## 5. Discussion

The project reorders and repurposes well-known elements of the architectural design to production processes. While interaction with physical objects is a normal process for humans, operating digital design interfaces requires a mental acquisition of certain skill set. Therefore, parametric modeling software was removed from the front end of the design process and wooden lamellas served as design interface.

The design of the lamellas as geometric input for the parametric design tool interweaved material sensitive design with computational materialization processes. The computational tool used the sensed input lamellas and derived a series of gradually differentiated lamellas by interpolating the two extreme ends for the robotically fabricated demonstrator. Moreover, the robotically placed rods can be understood as the generators within the ruled surface of the lamellas, connecting digital and real-world geometries with the same principles. Thereby, connecting the computational logic with the material realization possibilities enabled by a robot (Gramazio and Kohler, 2008).

The 3d scanned lamellas at the front together with the robotic fabrication process allow for a responsive design and fabrication process which is a process described by Felix Raspall through sensing, controlling and actuation to address uncertainties within construction processes (Raspall, 2015). In addition to that, we look at how design intentions can be shared between man and machine through real-world geometry.

The assembly process was divided by identifying abilities of the two involved actors, human and robot. Contemplating the complexity of architectural fabrication realities which are often so elaborate that though, we might not fully automate them, we get assistance at decisive moments (Helm 2014). The demonstrator shows these moments and illustrates a clear division of tasks while integrating them into one collaborative process (Figure 15).

In 2014 Mahesh Daas presented a taxonomy of a broad range of robotic applications in architecture. One framework defines different modes of interaction between man and machine. It states it as a field of research in which one refines the modes of human-robot interactions (Daas, 2014). Our research explores those modes and emphasizes the importance of man-machine collaboration in architecture.

The collaborative assembly showed a successful implementation of task-shaping between man and machine (Figure 16). However, the synchronous collaboration between man and machine may become even more relevant with a real-time implementation to enable updates of the manufacturing data based on subsequently placed lamellas.

In the field of robotics in architecture much research focuses on integrating machines via real-time feedback and agent-based systems into materialization processes. Achim Menges describes the concept of cyber-physical systems in which "[…] the behavioral machine may not even remain external to what is made, but become fully embedded and absorbed in the system to be constructed" (Menges, 2015). Our research makes a contribution by reordering the roles of the different actors within such a system. Additionally, we developed a methodology for digitization of materially computed geometries for correlating construction and design environment.

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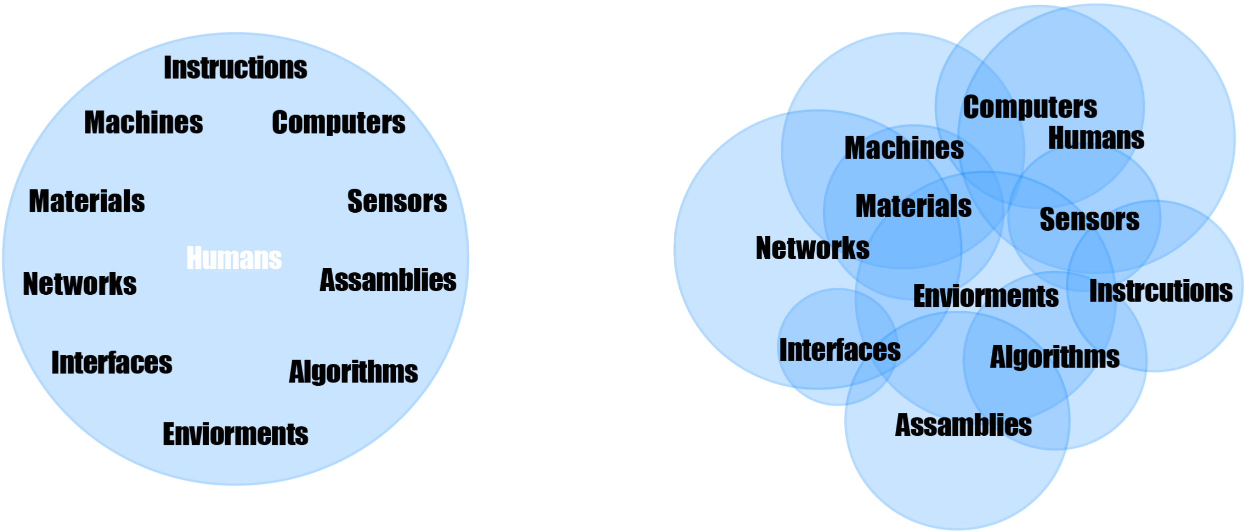


**Figure 15.**
Different models positioning humans within the architectural production framework. Left: All objects are oriented towards human operation from the background. Right: The humans is an equal participant within an agglomeration of actors.

**Figure 16.**
Placement of the last lamella.

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### 6. Conclusion and Future Work

This paper has presented a method for using real-world geometry that stays within the actual built construction as a design interface to start a man-machine collaborative process.

The 3d depth sensor was a first step of integrating sensing tools within the research, and can be continued for more complex feature extraction. Future research might apply more sensory data like force sensing and embed it as real-time feedback. The integration of such sensors in a collaborative processes would allow faster updates and interactions (Dörfler, Rist and Rust, 2013).

The collaborative construction illustrates possibilities of task-shaping due to the agents' capabilities. Our research suggests, that collaborative coexistence between man and machines does not have to end with the construction of one possible configuration, but can rather be an ongoing process of continuous temporality. Thereby humans are becoming the key environmental factor within the materialization process and participation in a Behavioral Model as suggested by Theodor Spyropoulos (Spyropoulos 2016).

The demonstrator places the human as a participant within computational design and materialization systems. We were able to show a novel sensibility between the humans, real-world geometry, the computational design system and the robotic assembly process. The material components together with machine vision form a design interface that could be available not only for architects. It pushes the concept of cyber-physical systems towards stronger participation of the human factor through real-world geometry (Figure 14).

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