Interactive Assemblies

Man-Machine Collaboration through Building Components for As-Built Digital Models

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Abstract. This paper presents our concept, named Interactive Assemblies, which facilitates interaction between man and machine in construction process in which specially designed building components are used as a design interface. In our setup, users physically manipulate and reposition building components. The components, digitized by means of machine sensing, become a part of the design interface. Each of the three experiments included in this paper examines a different robotic sensor approach that helps transfer of data, including the position and shape of each component, back into the digital model. We investigate combinations of material systems (material computation, self-correcting assembly) and matching sensors. The accumulated data serves as input for design algorithms and generates robot tool paths for collaborative fabrication. Using real-world geometry to move from virtual design tools directly to physical interaction and back, our research proposes enhanced participation of human actors in robotic construction processes in architecture.

Keywords: Man-Machine Collaboration, Robotics, Machine Sensing, As-Built Modelling, Interactive Assemblies

1 Introduction

During the past few decades, the introduction of parametric digital tools into architecture has eased the designers' task when building complex geometries. Yet, the actual construction process often proves to be tedious and does not permit any changes that may become necessary.

The digitalisation of the assembly process is closing the gap between design and construction processes. Gramazio et al. argue that the introduction of robots has led to the ‘second digital age’ in architecture [1]. For many years now, industrial robots have been crucial agents in complex assembly processes, especially in the automobile industry. The robots with embedded processes work in lab-like factories and, throughout their lifecycle, run a limited set of processes. Architecture presents distinctly different challenges because construction does not happen in lab-like factories. Complete automation in construction is unthinkable because uncertainties of construction work and cluttered work sites often present unanticipated difficulties that pure automation could not tackle. Such challenges might be addressed successfully by a collaborative processes of men and machines [2].

In recent years, we have seen inspiring research that tackles the issue of man-machine collaboration in architecture [3, 4, 5]. Most of the systems resulting from the research involve augmentation of the assembly processes. In these processes, either the user is instructed via augmented reality glasses or the robot is taught to follow specific gestures to behave in a certain way. The operation of this strategy, though impressive and novel, requires direct interaction between man and machine, which is a limiting factor.

We propose an alternative method for man-machine collaboration that leverages interaction through building parts and assemblies, using them as the interface between user and machine. In this paper we present the framework for this approach and name it ‘Interactive Assemblies (IA)’. IA challenges the conventional order of the design process leading to the construction processes and their typical workflows. IA consider the construction site as a source of inputs to the digital design model and depend on to and fro flow of information between the real world and the digital model. This communication involves the use of digital actuators, interfaces and sensors (Fig. 2).

IA contributes to the study of cyber-physical systems (CPS) with methods that promote the interaction between man and machine. CPS are ‘physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core’ [6]. The IA framework blends human users into the CPS through interaction with the building parts, which necessitates development of new modes of collaboration between man and machine.

Parametric modelling software based on generative geometries enable architects to manipulate geometries throughout the design process. Following the paradigm of parametric modelling software, IA connect cutting-edge computational design methods and the use of robotics in on-site construction methods to enable users to manipulate assemblies after or during their construction. [7].

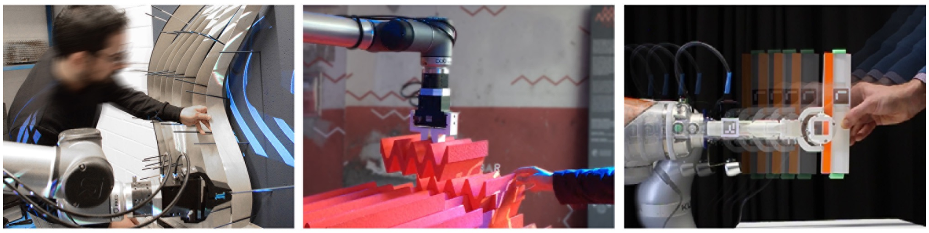

Fig. 1. Three experiments of interactive assemblies illustrating our approach in relation to different building components.

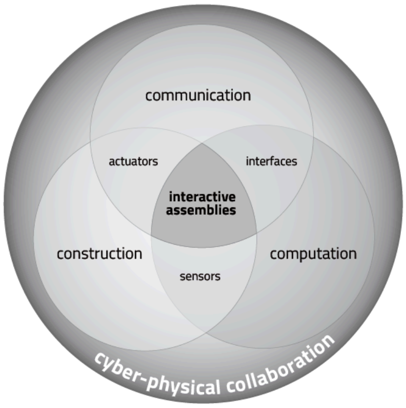

Fig. 2. Conceptual diagram of Interactive Assemblies and its components.

Our contributions to man-machine collaboration research on robotics in architecture are:

- Implementations of sensor technologies to transfer as-built states into digital design models
- Three different collaboration scenarios that use real-world geometry as inputs to a computational design tool (Fig. 1)
- Material systems that allow for user input and robotic assembly

2 Background

Considerable research has been conducted in the field of on-site robotic assembly [8, 9]. However, early attempts were built around paradigms of standardization or removing margins of error out of the production processes. Today's shift towards the digital paradigm puts *'focus on robotic fabrication turned towards the use of non-standard and non-discrete building material, the integration with conventional manual processes or the potential adaptability to dynamic environments (...)'* [10]. The use of robotic manipulators to procedurally inform indeterminate material processes through machine vision has been explored in projects like Remote Material Deposition [10].

Menges advanced the hypothesis that new technologies, through the introduction of cyber-physical systems, will lead to a conceptual transformation in architecture [11]. In the research conducted at the Institute for Computational Design and Construction (ICD), this concept was used to feed data from the materialization process back into the digital system via sensors. Their workshop project 'Robot-Assisted Assembly in Wood Construction' in 2015 illustrated a clear division of labour between man and machine. Nevertheless, design input by the users is not the key challenge within the process [12].

In architecture, robotics enables material realizations and assemblies that utilize computational logic [13]. After a review of the varied preceding research in this field, this paper investigates the potential of existing technologies and placement principles with a focus on man-machine collaboration during assembly processes and further, examines how as-built data can flow back into the design or planning model.

2.1 Man-Machine Collaboration

In the following paragraphs we present previous research on robotic construction in architecture focusing on man-machine collaboration.

Fukuda et al. discussed how, during construction in collaborative modes, humans can guide and teach robotic manipulators through sensors [14]. Helm has shown how gestures can be used to guide the placement of bricks by a robot [15]. Stumm et al. investigated the peg in a hole problem of wooden sticks and addressed it through dynamic compliance [16].

The concept for integrating human interventions into manufacturing process has been explored in an experiment of piling up wooden sticks with an industrial robot [17]. Among the crucial components of these man-machine interactions are real-time feedback through sensory data and actuators operating in the physical environment.

Johns developed a workflow consisting of a robotic fabrication tool with sensor feedback that enables architects to design spontaneously and intuitively [18].

Rossi and Tessmann communicated assembly instructions between human designers and robotic assembler [19]. They used a vision system to track instructions coupled with geometric constraint modules. Their research suggests the use of discrete geometries with discrete connection possibilities to constrain the possible actions of the modules.

2.2 3D As-Built Modelling in Architecture

3D as-built modelling (e.g., BIM) is the process of mirroring or remodelling built structures into a digital model. It plays an important role in a wide range of civil engineering applications. This modelling process commonly starts with collecting 3D point clouds from sites of interest. This is crucial for the digitalisation of construction as it helps to compare the designed model with the actual built state of the construction.

There has been a tremendous amount of research in this field of matching the design and the built structure [20].

For construction, Feng et al. have examined how the computer vision approach can be used for autonomous assembly while maintaining sufficient data on the as-built state of the construction [21]. Amtsberg et al. demonstrated several approaches of using machine vison technologies to build with parts, the shape of which were unknown when the construction started [22].

Research by numerous scholars has demonstrated that 3D point clouds captured from real world geometries hold sufficient data to generate CAD-like geometric models. For example, an application of a long distance laser scanning technology to facilitate a real-time parametric BIM Isomodel has been developed [23]. Furthermore, a semi-automatic approach for the 3D reconstruction of existing buildings from point clouds in the context of BIM has been explored. [24].

3 Methodology

Our approach to interactive assemblies and their processes consist of three main parts. First, the physical setup consists of the robot and building parts. Second, the digital setup that orchestrates the tasks and merges computational tools with sensor readings. Lastly, the collaborative modes depend on information exchanged between man and machine.

When designing and fabricating interactive assemblies several steps need to be imbedded into one workflow (Fig. 3). To develop this workflow, we asked the following questions: What benefits can designers get from real-world feedback? When and how should the feedback be used? What kind of information is relevant? And how do these processes influence the design?

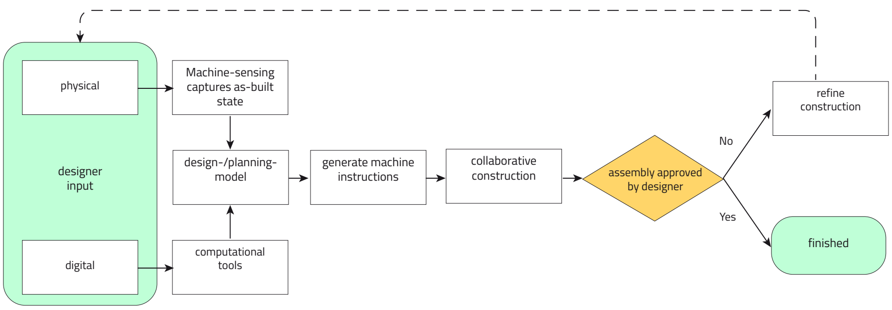

Fig. 3. Flow diagram illustrating how inputs by the designer can be derived from both the physical and digital.

The workflow starts with a design input. This input can be either digital or physical. We tested this workflow through three experiments on different approaches of man-machine interaction, sensor technologies, and building parts. Going through conceptualization and materialization generated valuable insights.

3.1 Robots, Sensors and Building Components

All projects made use of robot arms, a Universal Robots UR10, and Kuka Iiwa. Robotic arms mimic the geometrical features of a human arm and thus can share a similar work and task space. Moreover, both robots are approved for human-robot collaboration (HRC).

We set up different workflows to extract real-world data from the interactive assemblies. We pursued three strategies: A machine vision setup for 3D scanning, a vision system based on the interpretation of 2d images, and the repurposing of a robot as a digitizer arm that helps to precisely locate an object's position in space (Fig. 4).

The machine vision setup was based on a Microsoft Kinect V2 depth camera mounted on a UR10 to enlarge the range and viewing angles of the camera. We used the teaching function of the robot for digitization of building part positions. On pressing the free-drive button on the back of the control panel, the robot switches to compliance mode in which the human users can manually move the robot to any reachable position. The robot reports back the position of the tool tip as xyz-coordinates.

The Kuka Iiwa uses a FingerVision sensor for tactile sensing of forces and to detect the slipping of objects based on the research by Yamaguchi and Atkeson [25]. We imbedded the sensor into the finger of an electronic Sake EZGripper. The finger consists of a transparent silicon bed with an embedded grid of black dots that is mounted in front of a camera sensor. If something is grasped it can be visually recognised inside the gripper. When an object is grasped by the arm, the silicon bed is pressed against the object and is distorted by the pressure. This causes the distortion of the grid of the black dots, which is captured by the camera.

The three interactive assemblies are utilised to manipulate different building components, namely, wooden lamellas that can be manipulated by bending and twisting; corrugated foam blocks, and wall like elements, which can be placed between slabs. We tested the interactive assemblies for handling components placed in a range of positions and configurations in a continuous space. This meant, the components were not in predetermined positions in relation with each other. The interactive assemblies permitted some degree of freedom in the placement of the components.

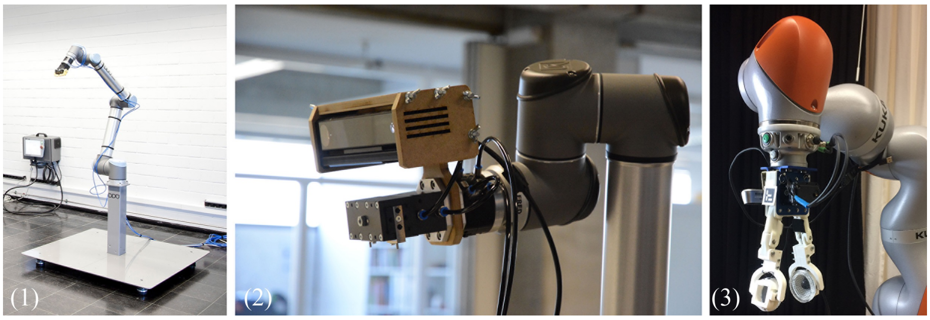

Fig. 4. Robots with different sensor types: position sensor for self-aware location picking (1), Microsoft Kinect V2 depth camera (2), FingerVision gripper for force and slippage detection (3)

3.2 Digital Setup

We used Rhino and Grasshopper to orchestrate the design models and algorithms for the experiments. We used Grasshopper to link data readings from sensors back into the architectural CAD modelling environment.

Different algorithms scaled and re-orientated point clouds from the Kinect and the ArUco marker readings. The robot operating system (ROS) communicated the states of the joints of the robot and translated those into positions of the building components in space.

For generating and uploading the robot program to the Universal UR10 robots we used Robots by Vicente Soler [26]. We programmed the Kuka Iiwa using the Robcom Interface developed by the Autonomous System Lab at TU Darmstadt.

Firefly by Andrew Payne and Jason K. Johnson [27] streamed the Kinect 3D-depth camera readings into Rhino. The Volvox plugin by CITA [28] processed the captured point clouds and extracted necessary features like curvature of the lamellas.

The FingerVision sensor readings were algorithmically analysed to estimate forces and slippage of objects held by the gripper. Also, we developed a force and slippage feedback controller for the robot. The controller sensed the external forces applied to an object in the gripper. The system also senses the direction of the force to continue its application or stop the application at a certain threshold.

3.3 Collaborative Modes

One of the main reasons for using robots is to complement and amplify human capabilities and relieve human worker of tedious and arduous tasks. Such tasks that entail enduring repetitious tasks that call for precise geometric positioning of parts, variations in the positioning of parts and judging the positioning of the parts based on force feedback. Through our experiments, we identified such moments and implemented the robot where it would prove to be most beneficial due to its skills.

Task shaping describes how processes change through the integration of new technologies [5]. This concept puts focus on a goal-directed task analysis. While a robot can outperform a human in the tasks mentioned above, cognitive guidance by a human can strongly inform it. For our experiments, we designed the tasks to be suitable for integrating design decisions by the user.

The design decisions were captured through robotic sensing technologies. Negotiating the sensor technologies with the building parts lead to adjustments of the parts. We customised the parts by colour-coding certain features of the parts to improve the perception by the sensor system.

The digital model stores the sensor readings derived from the assembly. This model consisted of an algorithm that automatically generates the execution plan for the robot.

We implemented different possibilities for the users to alter the execution plan in the algorithms by tweaking numerical values. Furthermore, the algorithms monitored the execution to allow users to interrupt the execution in case of unforeseen occurrences.

4 Experiments

The main idea of this project was to use the build environment as a collaborative design environment by the use of machine sensed data, computational design tools and robotic effectors. In order to validate our ideas, we developed three experiments that evaluated different aspects of machine sensing for man-machine collaboration.

4.1 Digitizing Manipulated Parts

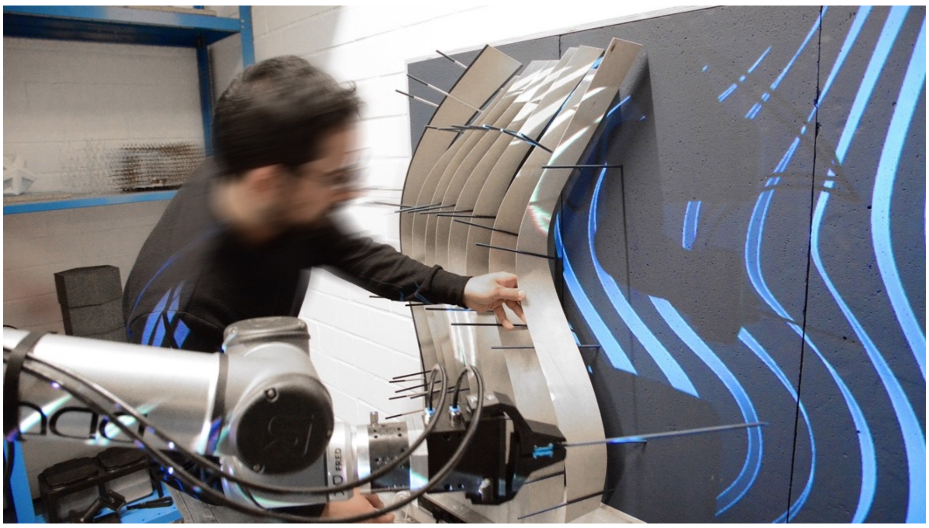

Fig. 5. Division of task in a collaboration assembly, composed of rods and lamellas and augmented by a projection.

The first experiment investigates design processes in which the specific geometrical configurations of the building parts are defined by the human designer. The process starts with physically manipulated lamellas that subsequently serve as an input into a design and fabrication algorithm. The goal is to understand how manual manipulation of a few initial building parts can generate design and fabrication data for all the related parts (Fig. 5).

In the experiment, the designer fixes two wooden lamellas to a foam board using rods. The rods can be rotated and positioned according to the surface, only the depth to which the rods were embedded in the board is predefined (Fig. 6). The robot 3D scanned the two manually formed lamellas at both ends of the board. We implemented an algorithm to generate a series of lamellas by equally dividing the distance between the scanned lamellas to place 18 lamellas (Fig. 7). We integrated a graphical interface to enable the users to manipulate geometrical features of the lamellas. Those include the positioning, orientation and rotation of the interpolated lamellas (Fig. 8). Furthermore, the algorithm automatically generates the code for the placement of the remaining rods by the robot.

Positioning and orientation of the rods for holding the digitally generated lamellas requires to be done with a high degree of precision. This task, if it were to be accomplished by a human, would require enormous amount of taking measurements and planning. However, a robot can easily be programmed for this task (Fig 10). In contrast, the placement of the lamellas requires much sensing by touch and coordination among the senses. Therefore, it was best performed by a human.

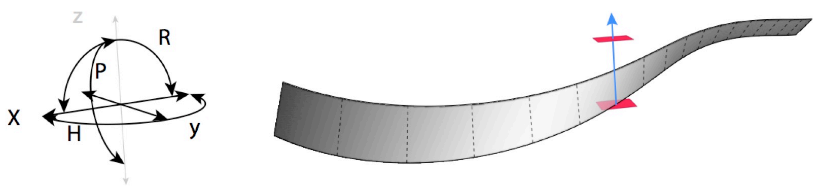

Fig. 6. Degrees of freedom of rods that are to be positioned by the robot following the geometrical principle of a ruled surface.

The key challenge of the first setup is understanding how to use as-built geometry even before the computational design and fabrication begins. The experiment illustrates how the human informed lamellas serve as the basis to generate the construction plan for the overall design.

Once the initial lamellas are placed by the designer and the assembly takes over the further task, the designer can still interact with the assembly digitally and physically as the process is repeated (Fig. 9).

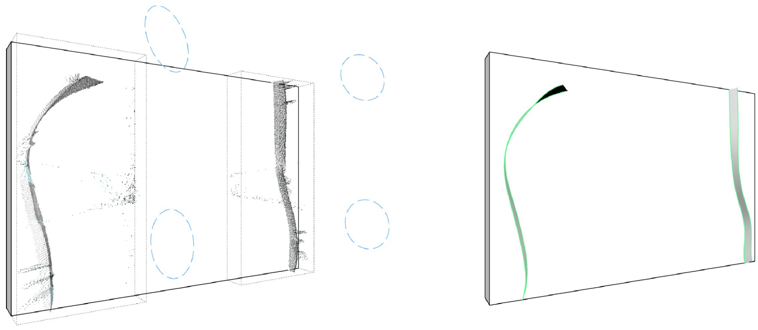

Fig. 7. Point clouds depicted from lamellas (1) and the extracted curves (2).

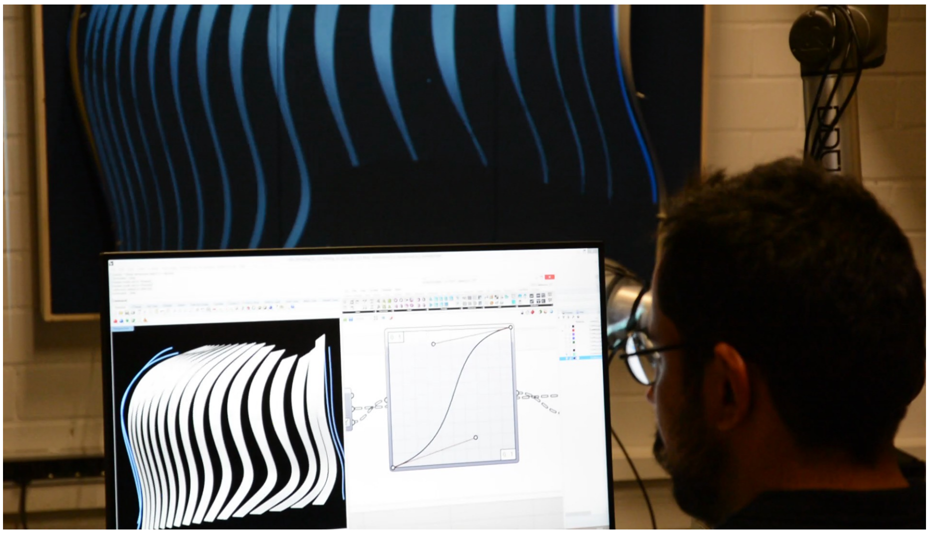

Fig. 8. Digital design interface utilizing graph mapper in Grasshopper for interpolation of lamellas.

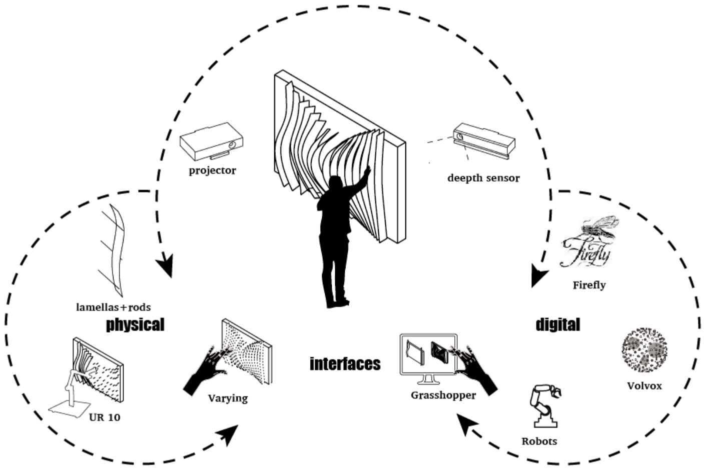

Fig. 9. The diagram illustrates the three tightly interwoven conceptual areas of the experiment: physical parts, computational tools, and interfaces with their designated elements.

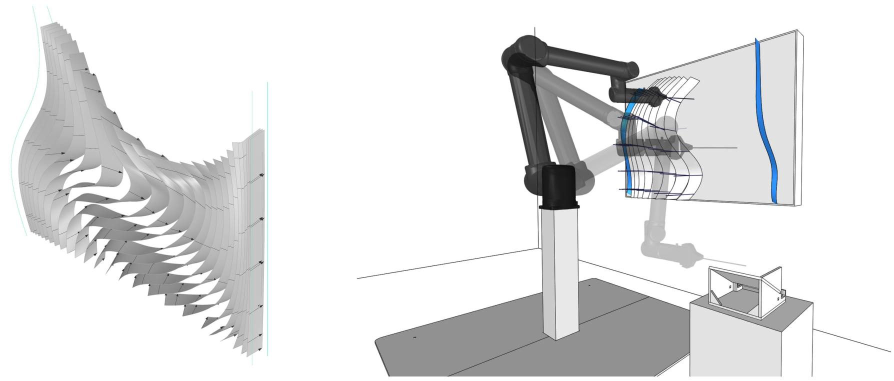

Fig. 8. Robot path generated based on the interpolated lamellas (1) and simulation of the robot program (2).

4.2 Digitizing Module Positions

Fig. 9. View of the installation during the light festival. The robot is relocating a module.

The key challenge of the second experiment was to understand how module positions of an interactive assembly can be digitized for a digital model. The task was to aggregate 400 corrugated foam modules into a shape-changing sculpture for a light festival (Fig.11). The UR 10 robot is an integral part of the installation to continuously re-assemble the module aggregation (Fig.12) to cause the anamorphic paintings that are spread over several modules to change their shape and meaning (Fig.17).

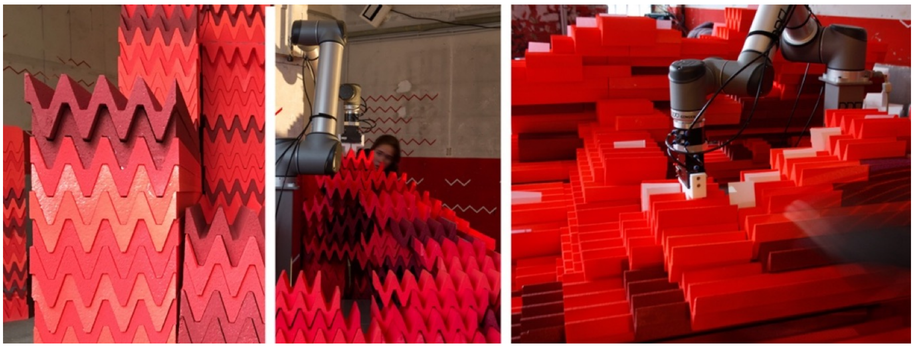

Fig. 10. Modules in compact arrangement (1), robot in compliance mode to capture module position (2), top layer of modules marked for robotic repositioning (3)

The robot executes the repetitive task of circular repositioning of the modules. The modules have self-calibrating connections in two directions to allow their stacking. One degree of freedom is provided to slide modules along x axis (Fig.14).

We pre-installed the installation in controlled lab conditions. On site, however, the geometry deviated from the initial setup, which called for precise xyz positions of modules in space to be digitized before running the re-assembly process. Here the industrial robot served as the digitizer arm. This is a commonly used method to digitalize models [29]. When the robot is put into compliance mode (Fig. 15) the brakes of the joints are released and the robot can be manipulated by hand. Whenever needed the exact xyz position of the tool tip can be recorded and transmitted through a WebSocket connection from the robot's controller via ROS to Grasshopper and, subsequently, to the Rhino model (Fig. 13).

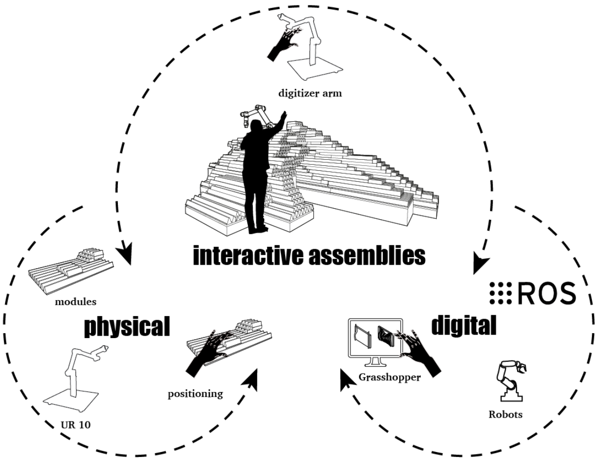

Fig. 11. The diagram shows the different elements and actions within the workflow of the experiment.

The process recorded and merged all module positions back into the digital model with sufficient accuracy. This enabled the designers to regenerate a digital model from a physical assembly, which challenges the usual workflow in digital manufacturing and offers novel approaches of designing in the context of an existing structure. Once digitized, the 3d model could be further developed from here with the broad variety of digital design tools available in Rhino 3D and Grasshopper. Additionally, captured setups can be stored and compared in 3D using the visual user interface.

From the digitalized positions the robot toolpath is generated automatically. It is composed of the captured input planes as well as a surface restricting the paths to avoid obstacles, forcing the robot to move only on paths along this surface (Fig. 16). The designer can choose the sequence for reassembling the modules. The program and distribution of modules allows for a looped reassembly process over several hours in the exhibition context.

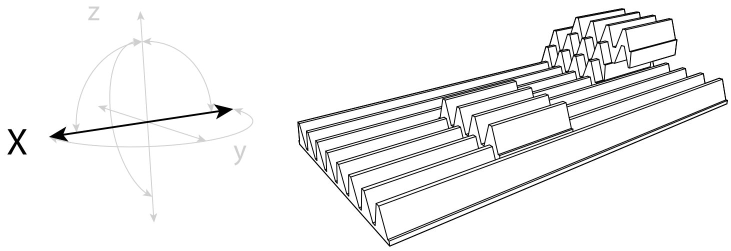

Fig. 12. Self-calibrating modular system with one degree of freedom.

Fig. 13. Digitization of new module position in compliance mode: human places a new module (1), human moves robot to location of module (2), new position is saved (3).

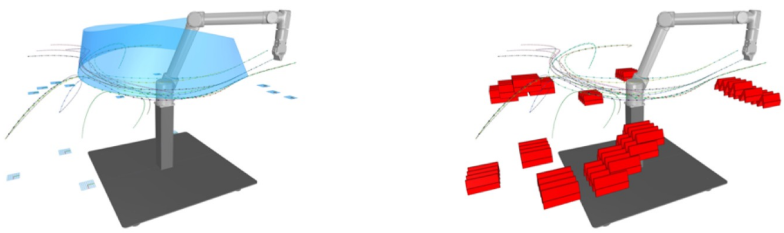

Fig. 14. Depicted planes from the assembly and surface constraining the robot path (1), digital representation of taught module positions (2).

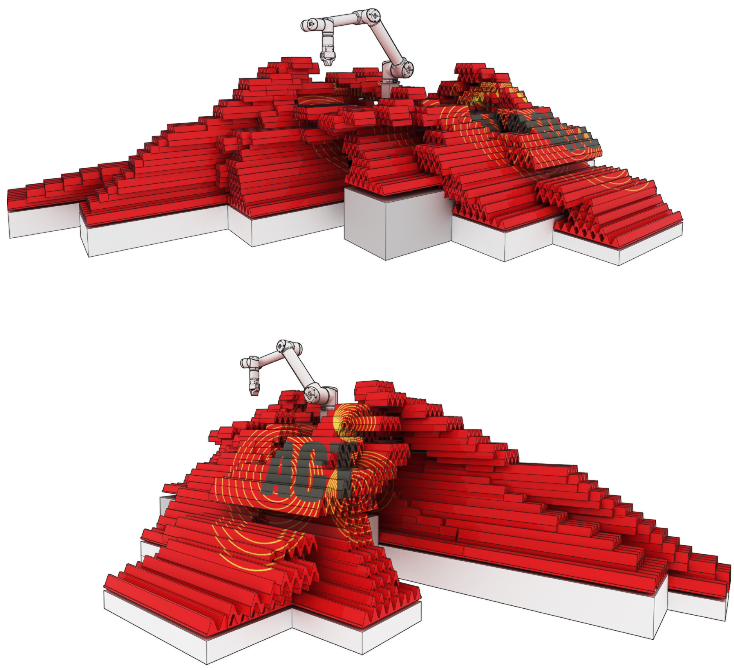

Fig. 15. Illustration of the anamorphic effect. The text "ACT" is not visible (top) until one reach the designated viewpoint (bottom).

4.3 Forces – FingerVision

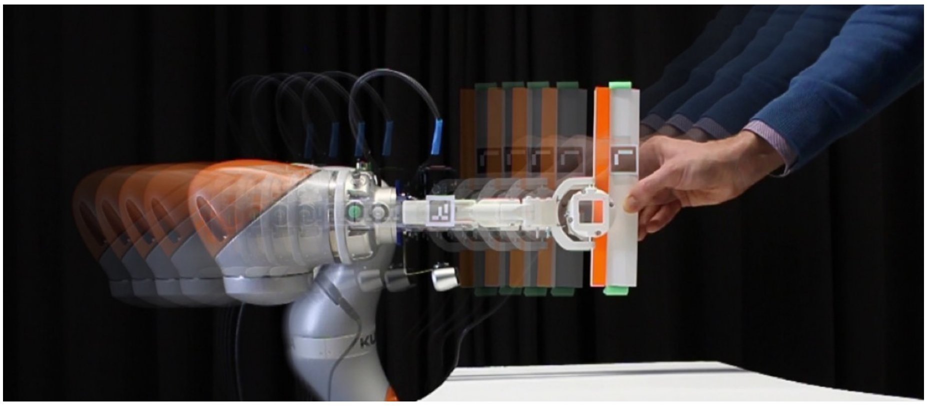

Fig. 16. Human applying force by pulling the object and robot following in the desired direction.

The third experiment explores real-time collaboration between man and machine. This collaborative system can cope with various and uncertain construction environments through real-time feedback from the sensor. Humans, robots, and building elements interact simultaneously to achieve a desired placement of wall like parts (Fig.18).

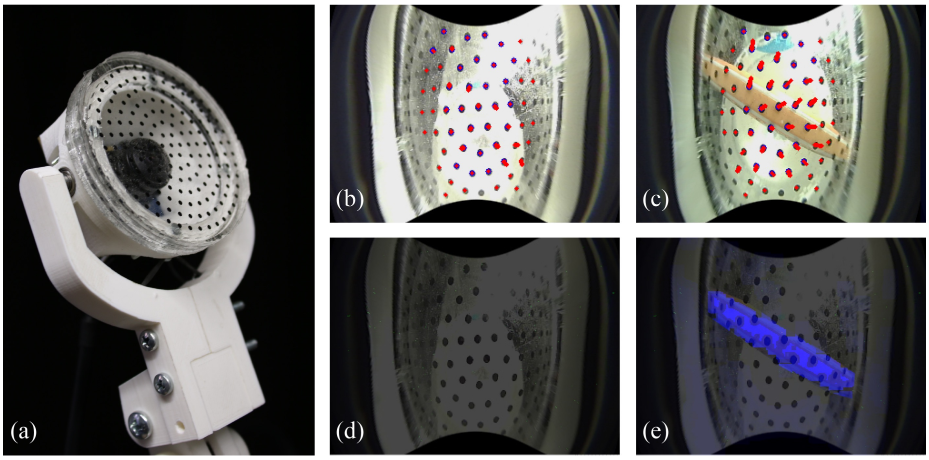

Fig. 17. The camera image from the Finger Vision sensor (a). Blob detection with no object (b), applied force to an object, red lines indicate the measurements in the direction (c), no object in slip-detection mode (d) and an inserted object recognized by the sensor, blue pixels shows the object (e).

The developed FingerVision sensor allows to determine the orientation and location of a part within the robotic gripper. Through a blob- and slippage-detection algorithm the forces applied to the part being grasped can be calculated (Fig. 19). The robot controller calculates paths on the fly enabling real-time feedback between the human operator and robot.

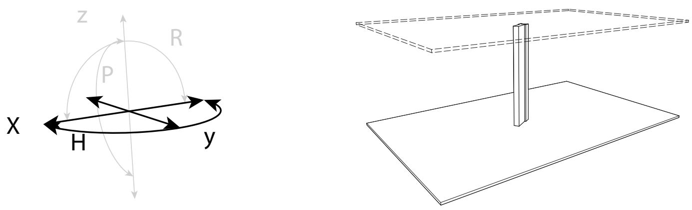

Fig. 18. Three degrees of freedom of wall element being placed between two slabs.

The human co-worker can pull parts into desired positions while the robot keeps the grasp. Thereby, this system serves as a small-scale version of a potential setup in which the robot's power is used to relocate heavy parts while being guided by humans.

In our experiment we tested the robotic insertion of a building element under a deformed slab. Simulating a scenario in which the deformation might be unknown, thus it illustrates uncertainties on sites. The robotic controller is programmed to insert the element between the slabs. It pushes the part along the slabs measuring the force and stopping when a certain threshold is achieved (Fig. 21). The wall elements can be placed in any orientation or position between the slabs in the xy-plane (Fig. 20).

An ArUco marker vision setup is used to evaluate the placement of the parts. A Rhino and Grasshopper file orchestrated the assembly and visualized the as-built positions of the wall parts (Fig.22).

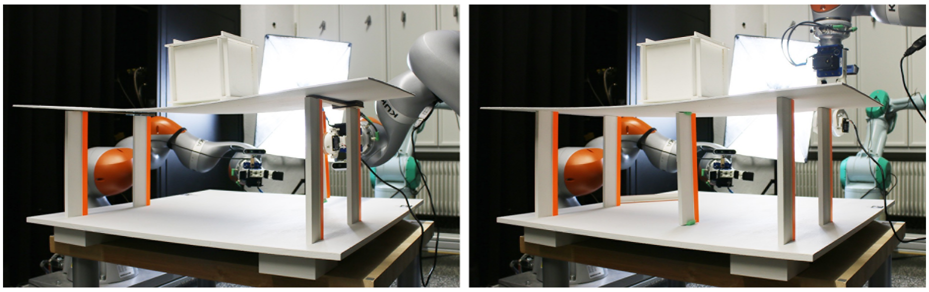

Fig. 19. The deformed slab without any support (1) and a wall component inserted below the point with the highest load (2).

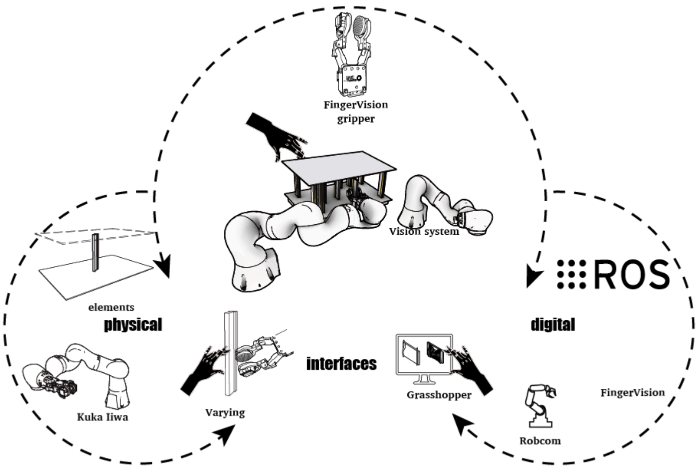

Fig. 20. The involved parties and action of the Finger Vision experiment.

5 Conclusion

The realities in architectural fabrication are often so intricate that we may not be able to fully automate them without giving the automated system human assistance at decisive moments [15]. Our research reflects the complexity of the realities in architectural production and suggests the subdivision of the assembly processes into series of connected steps. We identified the different abilities of the two involved actors, human and machine, for appropriate assignments of tasks. The experiments showed the decisive moments and illustrated a clear division of tasks even while integrating them into one collaborative process. Thus, opening up the discussion for explorations of those modes and the role of man-machine collaboration in architecture.

The experiments showed that the shape, orientation or position of building components can be communicated back into the digital model. Which information should be captured depends on the parts being manipulated by the human. Enriching the digital CAD environment with as-built information, the construction site becomes an interface.

The demonstrators orchestrated the involved parties in collaborative construction processes. We tackled the role of the human, not as an operator of a machine, but as an equal participant in the building process. While typically designed process are informed by simulation, we instead put emphasis on the users, directly designing with the building parts. Broadening the design interface and collaboration between man and machine into the physical realm, pushed the concept of *cyber-physical system* towards a stronger participation of the human factor.

The future research will have to investigate how to combine different sensor concepts for man-machine collaboration. The as-built approach captures different states of a construction site or even a building in use. This will make it necessary to think of a notation system for those states. Moreover, the different actors have to be choreographed and they will need to communicate to each other.

We showed a novel sensibility between the human, the building components, the computational design system and the robotic assembly process. The flow of real-world data back into a digital model for design procedures will help to augment both the physical and the digital world. We placed humans as active participants within computational design and materialisation systems. The material components together with the machine sensing form a design and construction framework that might be available not only for architects.

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