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Optical Parametric Component Referencing for the Facilitated Prefabrication of Timber Wall Elements

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Abstract

A guidance system for three-dimensionally accurate projections of timber frame construction elements was developed. Employing augmented reality (AR) glasses, interactive assembly instructions are projected onto the work environment of a timber construction company and integrated into their operational workflow. The purpose of this was to restructure the conventional assembly process utilising paper plans into a semi-digital, temporally relevant and accelerated process. The necessary geometry data was readily available and could be exported by current timber construction-specific CAD systems. The component information and layering sequence were configured for the glasses using an AR toolkit. Compared to preceding systems, the developed solution applies a successive relevant temporal filter as well as a fitting algorithm that refers to several localisation markers. Specifically developed software facilitates the levelling of the projection plane, measuring functions as well as approval and monitoring functions of individual components. According to practical trial runs of the assembly process, it was found that the project significantly improved the positioning of the individual timbers, the fastening of the sheeting and the insulation panels, while also reducing the extent of accumulative errors. Further development also managed to include non-conventional, free-form geometries. Tests revealed that the developed solution did not require any extensive training and its application could be considered intuitive.

Keywords: prefabricated timber structures, digital transformation, augmented reality, timber frame, design for manufacturing and assembly, precision, projection

1. Introduction

The duration of the manufacturing process of wooden panel elements strongly depends on the technical equipment of the respective timber construction company [1], [2]. The joint research project OptiPaRef (funded by the BMEL within the ZIM funding program 2021/2022) has therefore set itself the goal of increasing manufacturing efficiency and process reliability in the manual production of timber frame construction elements by making the low-investment technology of augmented reality (AR) usable for timber construction. To this end, the FLEX research group led by Prof. Dr.-Ing. Alexander Stahr has developed an assistance system for the holographic display of complex manufacturing information.

All relevant data is already defined by timber engineers; afterwards the information exchange takes place via a predefined interface from the CAD program [1]. The core idea of the project is to make the already existing planning data available to the carpenters in the workshop with the help of optical-parametric component referencing. To this end only the information required for the current work step is displayed and scaled directly in the carpenter's field of vision using AR glasses. At the same time, quality assurance in production is significantly simplified by the AR-based documentation of already placed elements.

2. Timber element construction in the SME sector

Traditional timber frame construction is based on prefabrication of large building elements, which are only assembled at the construction site. Due to the multi-layered requirements (statics, thermal insulation, sound insulation, etc.), wood panel construction has a high complexity in its overall structure as well as in its individual elements [1]. This requires a considerable manufacturing effort, which must be implemented in a secure production process. Within the market sector, a strong price competition can be generated by few companies that are automating their manufacturing in portal processing machines. Such large-scale equipment requires considerable investment, which is not manageable for medium-sized companies [2], In general, large production facilities and machinery are not necessary for the manufacturing process. In Germany the large majority of timber construction companies is employing less than 20 employees, who are joining timber elements manually in their workshops [3].

Factory planning for the manual production of wood panel elements takes place digitally with the help of wood construction-specific, menu-driven CAD software. This software is capable of generating the plans for the assembly of the panel elements as well as the control data for numerically controlled joinery systems or nailing bridges. In the company of the project partner Holzbau Lepski, ready-tied lumber and wood-based panels (see Figure 1) have so far been laid out and joined in a manual process. The information from the digital planning is stored on printed plans and transferred and checked from these analogously. For marking out complex geometries or free-form shapes, such as those found in bat dormers, it is necessary to print dimensionally accurate copies of corresponding partial sections of the construction drawings and to arrange them over the work piece. This analogous intermediate step is very time-consuming.

An existing solution for the paperless transfer of assembly information are laser systems permanently installed above the work table, which project the component contours onto the work surface in two-dimensional projections. However, the projections do not offer the desired possibility of information retrieval and are associated with a location-bound assembly, from which the research project would like to free itself [4].

Figure 1: Person mounting a timber frame

Figure 2: Positioning-outlines, localisation marker, release button and object ID

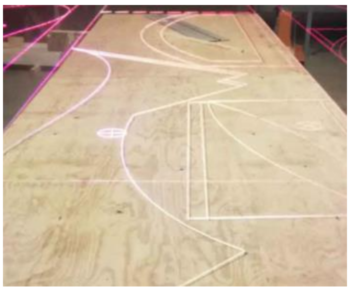

Figure 3: AR-Projection of free-form building parts onto LVL-boards

3. AR glasses instead of paper plans

In order to overcome these obstacles and to be able to offer an innovative, low-investment alternative, the project partners studied and further developed the application of AR glasses in the field of timber element construction [6], [7]. The overall goal was to extend the chain of digital planning data into the manufacturing process. The core of the work was therefore the description of a corresponding workflow and the development of interfaces, which ensure the availability of all information necessary for the assembly without time-consuming conversions.

This development was based on the HoloLens2 by Microsoft - AR glasses that use time-of-flight cameras to orient and locate themselves in space. With the help of a device-specific AR toolkit, special functionalities could be programmed to make the planning data already available in digital form directly and intuitively available to the workers during the production of the panels. Based on this, an action-oriented information structure was developed, which is based on geometry projection.

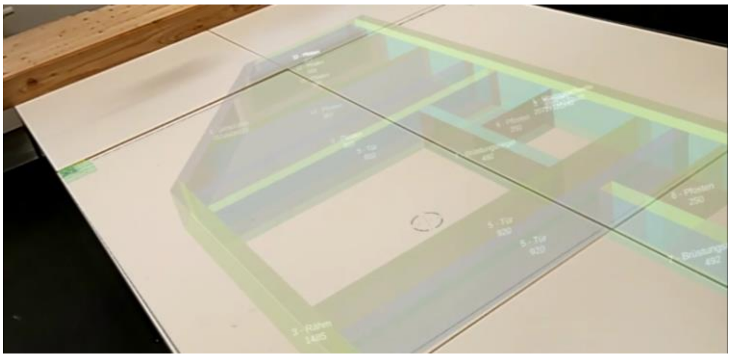

Figure 4: Geometry projection

In addition to the pure projection of target positions, a measuring tool was developed that processes information from the positions of a measuring marker (coordinates, lengths and angles) as well as an approval tool that enables paperless logging of the manufacturing process by means of gesture-controlled command input.

The multi-layered and written instructions that were initially envisaged proved not to be effective, as they severely restrict the worker's approach and his room for maneuver. Instead, the instructions are provided in purely geometric "information layers". Furthermore, it has proven useful to allow jumping back in the information sequences. This implies a shift from the term "instruction for action" to "possibility for action".

4. Setup and turning table

An element to be manufactured consists of a squared timber frame, which on both sides is clad with insulation, foils and boarding. This requires to turn the element. Due to the large dimensions, heavy weights and low stiffness of the unsheeted frame, a manual turning operation carries a high risk of damage or injury. Therefore, a butterfly turning table is used for this step, which consists of two adjacent assembly tables, a feeder table and a receiving table.

Figure 5: Butterfly turning table (feeder table)

The feeder table has a stop bar in the longitudinal direction and a clamping device in the transverse direction, by which the wooden frame is held in position. The individual parts of the wooden frame are positioned in it and joined together. This is followed by the planking and machining of the visible upper side of the frame with nailing or stapling machines; in addition, openings and holes can be cut in the planking.

Once the planking of one side is completed, the element is transferred to the receiving table by means of a hydraulically operated folding mechanism. To prevent collisions, the table has neither a stop nor a clamping device. These are not necessary for the dimensional stability of the element, as the frame is already connected. The second side can now be planked and machined here.

Figure 6: Sequence of butterfly turning table in action

5. Technical implementations

The FOLOGRAM toolkit (www.fologram.com) was used to control and program the HoloLens. FOLOGRAM is a mixed reality application that provides tools for processing 3D data and interpreting environmental data (e.g., QR markers, hands, spatial map, etc) on devices with autonomous location (e.g., smartphones, tablets, AR glasses). As its base, FOLOGRAM uses GRASSHOPPER, a node-based extension for parametric modeling under RHINOCEROS (www.rhino3d.com).

5.1. Precision of the Hololens

When switched on, the HoloLens generates a coordinate system from its current position. This means that the resulting coordinate system is unpredictable; however, the origin of the coordinate system can optionally be bound to a QR marker [4], [5]. From the sensor data, an environment model is created with respect to the coordinate system, the so-called spatial map, in which the HoloLens can locate itself. The spatial map is permanently updated. When changing the position of the glasses, minimal deviations in the assignment of the spatial map to the coordinate system occur due to the noise of the sensor data. This results in visible shifts and rotations of the coordinate system over time, the so-called drift. The longer and more widespread the movements, the more drift occurs [6], [7].

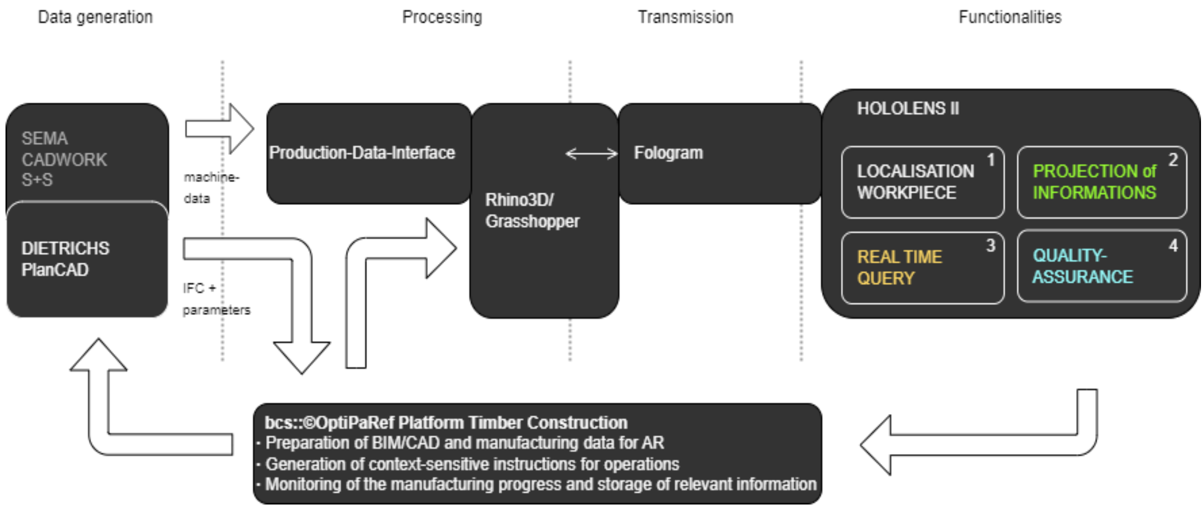

Figure 7: Data flow and required components

So the HoloLens-internal coordinate system is not suitable for millimeter-accurate positioning without a correction device (e.g. WLT tools for Unity) [8]. In addition, length measurements in space result in deviations of up to 1%. Measurements at different times result in different deviations. Therefore, precise position determination must be based on exactly defined reference points.

5.1.1 Positioning on the feeding table

Precisely measured, abrasion-resistant localization markers are attached to the feeding table, which are recognized by the HoloLens and matched with stored marker positions. Thus, the exact position and the scaling factor of the feeder table are unambiguous. Deviations from the target positions are displayed on a scale next to the marker. In this way, deviations caused by drift can be detected and corrected by re-reading the markers. The deviation of the projection to the physical components could be kept below 2mm over a length of the work table of 8 meters. This accuracy was considered sufficient for timber construction by project partner Lepski.

Figure 8: Abrasion-resistant localization markers

The markers are weighted in favor of the most recently read markers to account for the temporal effects of drift. To prevent all markers on the table from being covered by components, there are 2 markers placed on top of the stop bar at the end of the working area, which is usually never covered.

5.1.2. Positioning on the receiving table

After the turning process, the turned element rests in undetermined position on the receiving table. For integration into the digital workflow, however, its position must be precisely determined. This is achieved with the turning table markers that are placed on the corners of the turned element and read in. The lower corner closest to the stop bar of the feeder table defines the origin, the other corners define directions of the element. Since the four corners are oriented in different directions, the corresponding corner can be recognized from the marker orientation.

The positions of the markers on the receiving table are stored relative to the feeder table so that they can be removed again. This prevents the markers from being irreversibly buried under the plates mounted above them. To correct the drift, a marker could be read in at the encoder table.

5.1.3. Coordinate systems

The final positioning of the element takes place in relation to the clamping device integrated in the feeding table. The dimensionally accurate mapping of the element to be produced on the assembly tables requires the following coordinate spaces to be linked:

- HoloLens-internal (CS1), subject to drift
- CAD-related (CS2), origin of the geometry model
- Work tables (feeder and receiving table) (CS3), at a defined base point

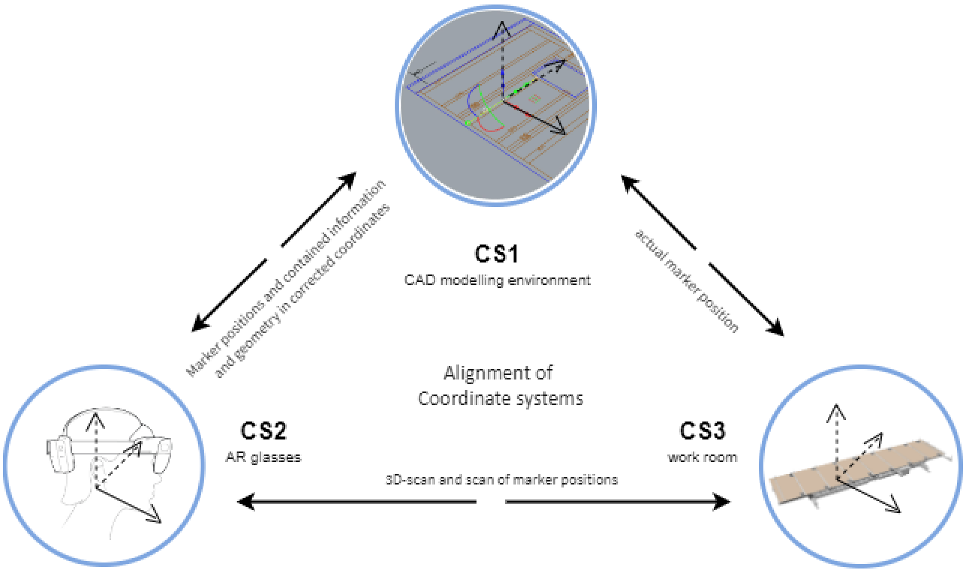

Figure 9: Relations between the coordinate

5.2. Interaction

The individual elements and functions that make up the system are shown below:

5.2.1. QR Marker Labels

A QR code ("Quick Response Code") is a two-dimensional barcode with integrated error correction, developed by the Japanese company Denso Wave in 1994. The HoloLens can determine the position of the markers in space as well as read out the information encoded in them. Depending on the strength of the error correction, even partially hidden markers can be read. The accuracy in determining the position of the markers varies with the environmental conditions (distance of the HoloLens to the marker, incidence of light, contrast). When observing a marker with the HoloLens, a wobbling of its image can be detected. This noise can be mitigated by calculating a mean value (median) from the last 25 marker positions determined.

Figure 10: Position marker, measure marker

Figure 11: Display of the user's hands

5.2.2. Control by hands

The HoloLens recognizes the user's hands and displays them in real time as a separate graphical element in the hologram. Coordinates can be extracted and processed from the geometry of the hand and the individual fingers, e.g. the position of the fingertip of a particular finger. If a fingertip comes close enough to a defined point, e.g. to the image of a control element, an action is triggered. To select an element, two fingertips are placed near the element in question.

5.2.3. Model Data

For the transfer of data from the element construction CAD program, an interface was casted which would fulfill the following requirements:

- universal, supported by as many CAD programs as possible
- complete, with all production-relevant information
- text-based for easier evaluation and, if necessary, extension

The WUP format from the Homag/Weinmann Company met all these requirements. It was especially developed for element construction systems. It is ASCII based and well documented.

Figure 12: 3D geometry of a bat dormer

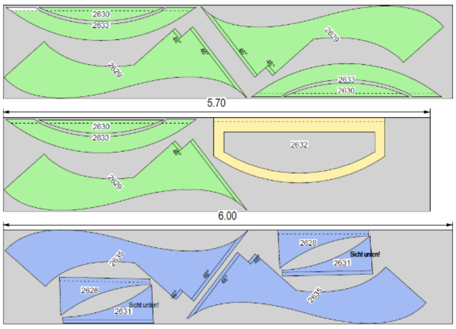

Figure 13: Placement of the curves within the measurements of the sheets

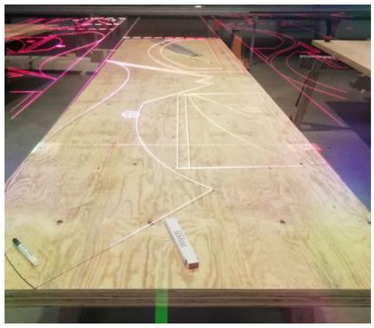

Figure 14: Projection of the outlines via AR device

In order to be able to use the positioning system for geometries other than wood-frame construction elements, a second projection interface was programmed which makes it possible to place any geometries from RHINOCEROS on the feeder table. It is designed only for tracing the outline of freeform geometries but not for interaction. For test purposes, the cut curves of a bat dormer were projected and drawn on raw boards (see Figure 14). The resulting measurements of the cut out building parts were all within the required range of precision.

6 Usage

6.1. Positioning and labeling

The original idea of displaying the element edges as lines along which the components can be aligned did not prove to be effective, since the line thickness must represent several millimeters for sufficient recognizability. Therefore, individual parts were broken down into their individual surfaces, which were colored differently. The component edges could thus be precisely positioned along the edges of the color transitions.

Figure 15: Coloured line display style

Figure 16: White line display style

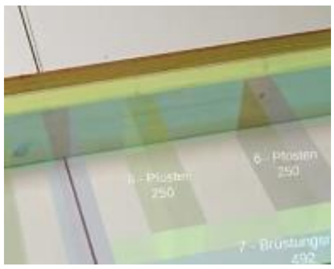

Figure 17: Surface display style

Since most of the individual parts have box geometry, 3 colors would be sufficient; i.e. one for each main plane. However, since there are also parts with oblique sections and individual parts connecting each other, 4 colors are used instead. Each part is randomly assigned 3 colors for the main planes and the fourth for slants. By using 4 colors, the probability that 2 coplanar faces of adjacent parts have the same color is reduced to 1:4. However, if situations arise where this is not sufficient, the random seed can be manually changed.

The component number and, if required, its designation are displayed to represent the individual part. It can be set whether the label is displayed only for the active part or for all parts. Machining operations are displayed with the values required by the operator, e.g. drilling diameter or setting values for the nailing machine.

6.2. Measuring

There is a separate QR marker for measuring lengths. It is placed at the point to be measured and read in with the HoloLens. As soon as the display has stabilized, a measuring point can be read in by touching the displayed measuring symbol with the hand (see Figure 18). By pressing the displayed reset symbol, the measuring points are reset and a new measurement can be performed. The quantity of read-in measuring points leads to different details:

- One measuring point shows the coordinates of the element origin (stop bar on clamping fixture).
- Two measuring points show the distance between these measuring points as well as the X, Y and Z distance in the coordinate system of the work table.
- Three measuring points show a triangle with distances and angles
- Four measuring points show a quadrilateral with distances and angles as well as the diagonal distances.

Figure 18: Measuring marker displaying set and reset-buttons

Figure 19: Selected element with approval button

6.3. Approval and documentation

After selecting a specific part with 2 fingers, it is highlighted and a detailed description is displayed. In addition, approval symbols are displayed, which can be activated with the hand. In this case the part gets documented in a text file. After the approval, only the outlines of the part are displayed and it can no longer be selected. The explicit selection of any part is intended to prevent individual parts or machining operations from being overlooked.

The text file with the documentation of the used parts also pilots the display of the parts to be processed. The work progress is laid out as follows:

- From the start of assembly, all parts of the wooden frame are displayed on the feeding table as long as at least one part of the frame is still not approved.
- Once the frame is finished, one side of the planking is displayed until the last part has been inserted or the last machining operation has been performed here as well.
- The element can now be turned. After the turning process, the position of the element on the receiving table must be read in with the turning table markers.
- Once the position of the element on the receiving table is determined, remaining machining operations and parts are displayed.
- After all parts and machining operations to be documented have been released, the element display hides and the next element can be loaded for machining.

6.4. Several HoloLenses

When using multiple HoloLenses, it must be taken into account that each HoloLens uses its own calibration as well as its own coordinate system. To work with the required precision, a separate FOLOGRAM computer must be set up for each HoloLens. If the text files that control the program progress are stored on a network drive that is accessible to all FOLOGRAM computers, they can be used simultaneously on the same element. This setup process could not be performed by the workers.

6.5. Ergonomics and practical use

In general, the use of the HoloLens was received with curiosity and positive feedback by the workers. The interactive control as well as the measuring and approval processes were immediately understood and applied. However, the setup process was found to be very complicated by the workers. The following peculiarities were documented:

1) Safety at Work: Particular hearing protection that can be worn together with the HoloLens is available for use in factory halls.

2) Power: The low battery power of the HoloLens was found to be problematic. However, this can be remedied with an additional battery worn on the body.

3) Robustness: When using tools with strong vibrations or large chip ejection, the HoloLens is irritated. In these cases, the contour to be produced was traced with a pen and then produced without HoloLens. After removing and putting away, the screen was occasionally forgotten to be folded up, after which the system was automatically put into sleep mode and then had to be restarted.

4) Wearing Comfort: For the duration of the test scenarios of a few hours, continued wearing of the HoloLens was not a problem. It was not tested how the wearing comfort develops during a whole day or over several days.

7 Evaluation of assembly times

To document the reduction in assembly time, 2 elements with similar dimensions and the same number of individual parts were manufactured by two workers; one in conventional manual joinery and the other with AR glasses. While the conventional paper plan guided assembly of a standard timberframe wall took 1,5h, the AR-projection based assembly of the identical wall took only 46 min from the moment of uploading the geometry until the wall was finished.

8 Results

After embedding abrasion-resistant QR markers into the surface of the worktable, the deviation of the projection to the physical components with an accuracy that was deemed to be sufficient for timber construction by the project partner Holzbau Lepski.

The intuitive approach proved to be successful during the test runs carried out. Test subjects who had no experience in using AR solutions were able to intuitively operate and use the developed system without extensive training periods. Short explanations were sufficient for the use of the measuring and approval tools as well as for the markers for the turning table. Only startup and setup of the AR glasses required extensive training.

Although the glasses are not technically mature at this point, time savings based on AR projections in the digital continuation of planning can already be demonstrated.

9 Future Work

Recognition of components based on glued labels does not currently work because the markers required for recognition by the AR glasses do not fit on the slim surfaces of the wooden elements. In addition, the effort required to manually apply the labels (on multiple component sides) is not commensurate with the expected time savings. In a follow-up project, it would be recommended to investigate how a component marking generated with the help of numerically controlled joinery systems can be reliably read and recognized by the glasses. This way the correct placement of the marked component could be automatically identified. The development would result in additional quality control and further time savings. An additional increase in usability and simplification of the setup installation would be the renunciation of the proprietary software Grashopper and Fologram and to develop an open source app, which fulfills mentioned task steps.

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