Quality Control of Robotics Made Timber Plates

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SUMMARY

Wood is one of the oldest construction materials which human beings use. Nowadays it is getting more popular because wood is renewable. On the other hand, there are new developments in fabrication and design. However, an industrial robot can be used in timber construction. Researchers from the University of Stuttgart started a project to develop a wooden prototype building prefabricated by robotics. There is a low level of experience about how accurately wood can be processed. For that reason, one part of the project is the quality control of the prefabricated plates. 24 of 243 wooden plates are measured by a laser tracker. A fabrication accuracy of 0.4 mm in 2D is achieved. Statistical tests show that up to 4% of the measurements differ significantly from the CAD model. To make a statement about the behavior of the plate during storage, four plates are measured twice more, once before the transport to the building site and once after one night at the building side. In this paper, an example for one plate is given. This plate shows no deformations between production and after one night at the building site.

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1. INTRODUCTION

New developments in computational design offer new individual fabrication processes in timber construction. Industrial robots can be used in timber construction to develop new design approaches. But no statements about the accuracy which can be reached in these cases are available. However, quality control for a timber prototype building fabricated by robots has to be realized.
This paper presents a possibility how to check 24 individually fabricated and designed wooden plates for accuracy using a laser tracker.
The behavior of wood during storage is a point which is interesting for the timber constructor, because wood is a living material which can change over time. This is the reason why some of the plates are checked twice and even three times.

2. PROJECT DESCRIPTION

The investigations described in this paper, are part of the project *Robotic fabrication in Timber Construction*. It is a project driven by architects, structural and geodetic engineers of the University of Stuttgart together with industrial partners like timber fabricators and the federal state Baden-Württemberg. The goal is to develop a lightweight timber construction system which combines robotic fabrication with computational design and simulation processes (ICD, 2014).
A prototype is built at the horticultural show *Landesgartenschau 2014* in Schwäbisch Gmünd, Baden-Württemberg, Germany. The prototype is made of 243 timber plates made of beech plywood. These 50 millimeter thin plates are manufactured by an industrial robot with seven degrees of freedom. The plate structure of this prototype recalls the skeletal shell of a sand dollar, a species of sea urchins (Krieg, et al., 2014). The sand dollar has a skeletal shell of polygonal plates of calcium carbonate which “are joint by interlocking calcite protrusions that are the biological equivalent to man-made finger joints” (Krieg, et al., 2014). Each plate has an individual form and position. The form and position is calculated by an optimization and simulation process (Krieg, et al., 2014). The structure of the plates will be visible after setting up the prototype. Factors like statics and extension of the robot are considered. At the end, 7600 finger joints are produced. The pavilion shown in Fig. 1 has got a floor space of 125 m^2 and the surface envelope of 245 m^2, but there are only 12 m^3 of timber used (ICD, 2014) .

Fig. 1 a) Exterior view of the pavilion b) Plate structure ©ICD/ITKE/IIGS, University of Stuttgart.

One roll of the geodetic engineer is to give an idea about the reachable accuracy of the plates. The second step will be to investigate the plates regarding deformations between fabrication and composition. At last, there will be a deformation analysis of the whole prototype. This last step is not part of this paper.

3. LASER TRACKER

Laser trackers with their high distance accuracy and additional probing tools offer a lot of different capabilities. In this paper, the laser tracker API Radian from Automated Precision Inc. (API) is used together with the probing tool IntelliProbe360™. With that probing tool, shown in Fig. 3, it is possible to measure, for example, hidden points. The specialty of the laser tracker is the fact that it works with two kinds of distance measuring principles. On one hand, it can be used with the interferometric distance measuring method, which is based on the Michelson-Interferometer from 1881. This method offers an accuracy of 5 µm on 10 m. On the other hand it offers the absolute distance measuring method. This mode is the one which is used together with the IntelliProbe360™. The reason for this is that there is no so called birdbath, a known point signal by an adapter at the laser tracker (Fig. 2), for the IntelliProbe360™, which means that there is no known distance for the interferometric measuring method. The producer specifies an uncertainty in 3D points of ±126 µm for two sigma in a distance of 7 m for the absolute distance measuring (API, 2010).

Fig. 2 Laser tracker with the reflector in the birdbath.

Data acquisition with a laser tracker can be realized by different methods. For example, it is possible to measure discrete points, which means that one point, signaled by the reflector or IntelliProbe360™ is measured. Another data acquisition method is scanning. In this case, the reflector or probing tool is moved and a measurement will be made in a given distance or time.
For this kind of task a special tip is needed to measure the edges of the timber elements. The tip, shown in Fig. 3, is designed by the Institute of Engineering Geodesy Stuttgart, because there are no comparable tips available on the market. This tip offers the possibility to measure the point of the edges directly, whereupon the tip cannot slip down from the edge. Before the actual measuring task can start, the probing tip has to be tested. For that reason, the tip is tested on a metal work piece, which is produced with a fabrication standard deviation s_F of better than 0.1 mm in the workshop of IIGS. One of the edges of the work piece is measured ten times. From the deviations between the measurement values and the CAD model the s_F can be calculated. In this case the s_{FM} gives the accuracy of measurement and fabrication. However, since the fabrication accuracy is known, the measuring standard deviation s_M can be calculated as followed:

$$s_M = \sqrt{s_{FM}^2 - s_F^2} \quad (1)$$

With an average s_M of 0.132 mm in X-direction, 0.118 mm in Y-direction and 0.182 mm in Z-direction, the measuring accuracy is calculated. The measuring accuracy in X-direction is 0,086 mm, and in Y-direction it is 0,063 mm. However, the 2D-accuracy is 0,106 mm. The Z-direction is not important for the context of the project because it does not depend on the fabrication process. It depends on the behavior of the timber plates before or after fabrication.

Fig. 3 IntelliProbe360™ with the special designed tip.

4. MEASURING PROCESS

To get an overview about the accuracy of the plates, 24 plates of the 243 plates were quality controlled. The industry specification for timber fabrication is e,g. 4 mmtolerance for lengths of 1 m (DIN18203-3). According to a rule of thumb his yields to a standard deviations of 1 mm for fabrication (Witte & Schmidt, 2006). These specifications are not of importance for this project, since the fabrication of the plates cannot be restricted to length or cross section. A clear tolerance specification was not given by the partners. For measuring with the laser tracker, the software *Spatial Analyzer* from *New River Kinematics* is used to operate the laser tracker and to realize the analysis. First of all, the laser tracker has to be aligned to the plate. For that reason, the CAD model of the plate is integrated into Spatial Analyzer. The software offers a tool to align the Laser Tracker to the CAD model. This tool first uses the socalled 3-2-1-Transformation to find a common coordinate system between measurements and CAD model (New River Kinematics, 2013). Afterwards, a 6 Parameter-Transformation, which is called Best-Fit-Transformation, is done. The 3-2-1-Transformation calculates an approximate solution for stationing. This means a common coordinate system for CAD and the instrument is created. The first point measured or chosen is the origin. With the second point the x-axis is created and with the third point the xy-plane. The z-axis is orthogonal to the xy-plane (New River Kinematics, 2013). For this alignment, a Spherically Mounted Retroreflector (SMR) is used. In this case the laser tracker operates with the interferometric mode.
After the alignment, the edge points are measured. At each finger joint ten points are measured with the special designed tip for the IntelliProbe360™. At the outside section of the plates between three and six points are measured. An example for measured points is shown in Fig. 4. All these points are measured discretely. There is no scanning mode used.

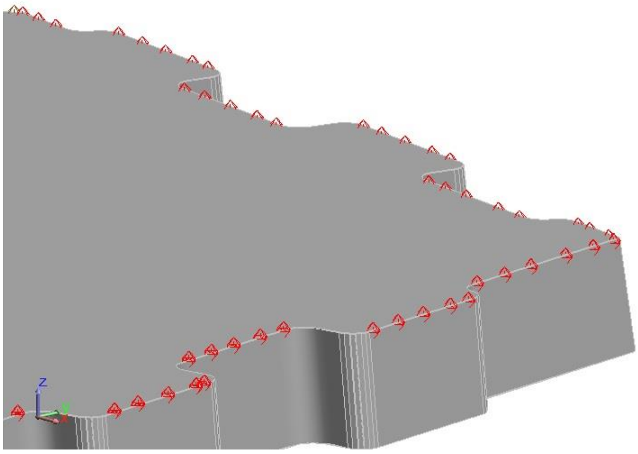

Fig. 4 Measurements.

After finishing the measurements, the deviations between the measurements and the CAD model are calculated by the Spatial Analyzer function *Relationship*. Plotting vectors of these deviations are visible. There are effects caused to the alignment. To minimize these effects, a function named *Minimizing Relationship* is used. This calculates the optimal parameters of a 6 parameter transformation by adjustment theory (New River Kinematics, 2013). An iterative algorithm minimizes the standard deviation (s_{FM}) over all measured points of one plate. The standard deviation is calculated as follows:

$$s_{FM} = \sqrt{\frac{l^2}{n}} \quad (2),$$

where l is the deviation between the measurements and the CAD model and n is the number of deviations. Global of deviations. Global systematic deviations are assumed to be eliminated, because of the before mentioned function before mentioned function Minimizing Relationship. Local systematic effects are randomized by this function. In

by this function. In

Fig. 5 an example of the deviations in 2D is shown. The color bar on the right side shows the absolute values of the deviations. Most of the deviations are between 0.001 mm and 0.352 mm. All deviations of the plate shown in Fig. 5, are pointing to the middle of the plate. Compare to the CAD, the plate is smaller than it should be.

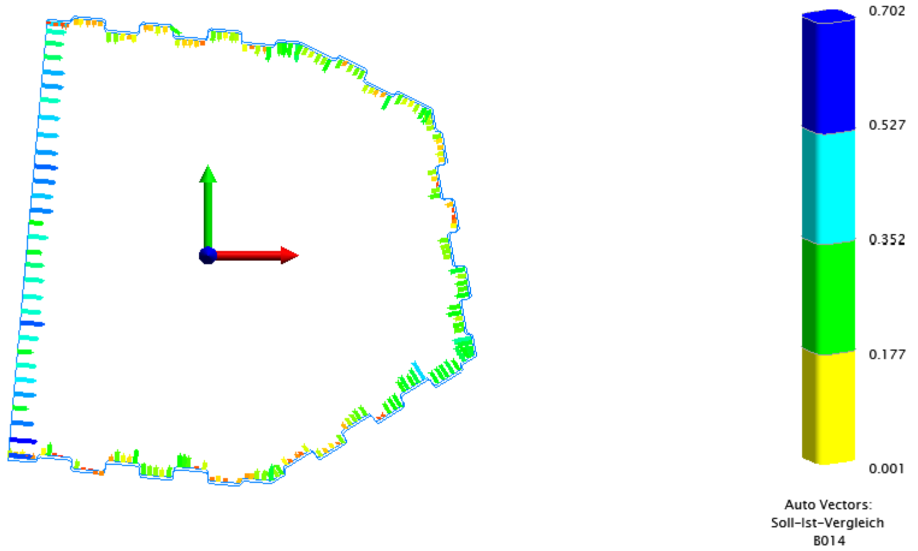

Fig. 5 Example of deviations in 2D.

After minimization, an average s_{FM} for all plates in X- and Y-direction is calculated. In X-direction the average s_{FM} is 0.292 mm and in X-direction it is 0.332 mm. Using the test measurement described in section 2, the fabrication accuracy is calculated. With the s_{FM} of the 24 measured plates the fabrication accuracy in X-direction is 0.28 mm and in Y-direction 0.32 mm. This results in a 2D fabrication accuracy of 0.42 mm. For the Z-direction the accuracy is not calculated because plywood has the tendency to buckle and dish (Krieg, et al., 2014). So the values in Z-direction are showing this effect, which is not a fabrication effect that is expected and does not reflect the fabrication accuracy.

5. QUALITY CONTROL AND ANALYSIS OF RESULTS

For the quality control it is interesting to know if the deviations between the CAD model and the measurement are significant. The measurements represent the fabricated plate. Significances are tested. For the test, the deviation between the CAD model and the measurement in each direction is divided through the s_{FM}. The test statistic is given by:

$$y = \frac{d_x}{s_{FM}} \quad (3)$$

where d_x is the deviation between CAD model and measurements. The null hypothesis is:

$$E(y) = 0, y \sim N(0,1) \tag{4}$$

The quantile for the null hypothesis is $y_{1-\frac{\alpha}{2}} = 1{,}96$, with a significance level of 5%. This double-sided test assumes the Gaussian distribution. At the current state of investigations, it is not clear if the distribution of the deviations is really Gaussian. This will be investigated in the future. If $y \leq y_{1-\frac{\alpha}{2}}$, the null hypothesis is accepted, which means that the deviations between the measurements and CAD model are not significant. If the test is not accepted, the deviations are significant. Within the measurement accuracy significant deviations between the CAD model and the measurement value are to be detected. In Tab. 1 the number of significant deviations in both directions and their percentage of values are given.

Tab. 1 Number of significant deviations and the percentage of values.

	X	Y
number	192	167
percentage	3,6 %	3,1 %

6. EXAMPLE FOR DEFORMATION ANALYSIS

Four of the 24 plates are measured three times, because the behavior of the timber after production, after a long term of storage and after the transport to the building site should be analyzed. The measurements on the building site where made in a carport which protects the laser tracker and the plates against solar radiation. The measuring and analysis process for these measurements is similar to the one for all 24 plates.
In Tab. 2 the s_{FM} per epoch and element is shown. The s_{FM} changes between the different epochs up to 0.19 mm. But the minimum and maximum cannot assign to a designated epoch.

Tab. 2 s_{FM} in different epochs.

plate 1	dx [mm]	dy [mm]	2d [mm]
epoch 1	0.346	0.393	0.524
epoch 2	0.286	0.550	0.620
epoch 3	0.301	0.479	0.566
plate 2	dx [mm]	dy [mm]	2d [mm]
epoch 1	0.505	0.508	0.716
epoch 2	0.532	0.470	0.710
epoch 3	0.408	0.281	0.495
plate 3	dx [mm]	dy [mm]	2d [mm]
epoch 1	0.306	0.210	0.371
epoch 2	0.307	0.191	0.362
epoch 3	0.458	0.264	0.529
plate 4	dx [mm]	dy [mm]	2d [mm]
epoch 1	0.277	0.439	0.519

epoch 2	0.316	0.531	0.618
epoch 3	0.296	0.564	0.637

For these measurements of the following epochs, each plate is tested statistically as described in section 5. The count of significant deviations is almost equal for the first two epochs. In the third epoch, there are more significant deviations in X- and Y-direction. The reason for that is not metrological and cannot be clarified in the current state of research.
By way of example, the results are shown for one plate and one epoch comparison. The first epoch is measured directly after fabrication and the second epoch is on the building site six weeks later. During these six weeks the plates were stored in a construction hall of the timber constructor.
To analyze the deformation between two epochs, one has to consider that it is not possible to measure the same point in both epochs. This is because the measured points could not be marked and the laser tracker works more or less area-wise. However, it is not possible to compare measurements. In this case, the average deviation $\bar{d}$ of the measurements from each inner and each outer side of the individual finger joint is calculated for both epochs. This average deviation is subtracted from each other and divided through the root square sum of the s_{FM} from both epochs. This test induces to a general statement about global deformation at the plate. The test statistic is given as:

$$y = \frac{|\bar{d}_{epoch1} - \bar{d}_{epoch3}|}{\sqrt{s^2_{FM_{epoch1}} + s^2_{FM_{epoch3}}}} \quad (5),$$

Like in the test from section 5, this test takes the Gaussian distribution as a basis with a significant level of 5%. In this case the quantile is $y_{1-\frac{\alpha}{2}} = 1.96$. If $y \leq y_{1-\frac{\alpha}{2}}$, the null hypothesis, which is $E(y) = 0, y \sim N(0,1)$, is accepted, which means that there are no deformations between the two epochs. Otherwise, if the null hypothesis is not accepted, there are deformations at the tested edge. The tested plate is plate 1 and the null hypothesis is accepted for all 52 edges. This means that there are no significant deformations between the two epochs.

7. CONCLUSION AND OUTLOOK

The investigation of this random sampling shows that a fabrication accuracy of 0.4 mm is reachable. This is caught with a 2D measurement accuracy of 0.11 mm.
The first test regarding the individual measurements shows the percentage of significant deviations at the individual plates is up to 4%. Nevertheless, the timber constructor had no problems to set up the prototype. These 4% may be caused by occur overlaps at the plates, where robotics did not work precisely enough or the plate dish or buckle, so that the robotics did not reach these edges.
In section 6, one plate is tested for deformations during storage. The test shows that there are no significant deformations during six week bearing. The test dealt with global deformations. Local deformations at the plate were not detected, since the points measured in the different epochs were not the same. Additionally they were not of interest the within this project. In the future modelling by splines or something similar should be used to detected local effects of the deformation behavior.

In the future it is interesting to investigate the movements of the prototype and to investigate the changes of the plugged plates. In addition, the deviations have to be investigated if they are really Gaussian distributed. Furthermore, new statistical tests have to be developed to give more precise statements about the deviations between the CAD and the measurements as soon as the deformation analysis is finished.

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