Working with Uncertainties: An Adaptive Fabrication Workflow for Bamboo Structures

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Abstract. This paper presents and investigates a cyber-physical fabrication workflow, which can respond to the deviations between built- and designed form in real-time with vision augmentation. We apply this method for large scale structures built from natural bamboo poles. Raw bamboo poles obtain evolutionarily optimized fibrous layouts ideally suitable for lightweight and sustainable building construction. Nevertheless, their intrinsically imprecise geometries pose a challenge for reliable, automated construction processes. Despite recent digital advancements, building with bamboo poles is still a labor-intensive task and restricted to building typologies where accuracy is of minor importance. The integration of structural bamboo poles with other building layers is often limited by tolerance issues at the interfaces, especially for large scale structures where deviations accumulate incrementally. To address these challenges, an adaptive fabrication process is developed, in which existing deviations can be compensated by changing the geometry of subsequent joints to iteratively correct the pose of further elements. A vision-based sensing system is employed to three-dimensionally scan the bamboo elements before and during construction. Computer vision algorithms are used to process and interpret the sensory data. The updated conditions are streamed to the computational model which computes tailor-made bending stiff joint geometries that can then be directly fabricated on-the-fly. In this paper, we contextualize our research and investigate the performance domains of the proposed workflow through initial fabrication tests. Several application scenarios are further proposed for full scale vision-augmented bamboo construction systems.

Keywords: Adaptive fabrication · Computer vision · Construction tolerance · Natural material · Bamboo

1 Introduction and Research Context

1.1 Natural Material and Construction

Global average temperature has increased by more than one degree Celsius since pre-industrial times. Recent research (Churkina et al. 2020) has shown that using bio-based construction materials with good carbon storage capacity, such as bamboo and timber, can be part of a solution for the global warming issue.

Raw bamboo has remarkable mechanical properties and is a high-yield renewable resource (Atanda 2015). Bamboo poles as a construction material has not only been extensively used in vernacular buildings in its growth regions, but also attracted a lot of interest of contemporary architects around the world, such as Vo Trong Nghia, Kengo Kuma, Simon Velez and Markus Heinsdorff (Fig. 1). Though it has been explored in different construction typologies, such as small-scale residential buildings and pavilions, its performative potentials have not been fully exploited and it is still most commonly used as scaffolding in the east-Asian regions. Previous studies have demonstrated the potential of bamboo for pre-engineered structures (Bhalla et al. 2017), but challenges still exist for the fabrication process.

Fig. 1. Bamboo in architecture. (a) Bb Home, Vietnam, 2013 (Image Source: H&P architects); (b) Vinata Bamboo Pavilion, Vietnam, 2018 (Image Source: VTN Architects/Hiroyuki Oki); (c) Bamboo pavilion for Expo Shanghai, China, 2010 (Image Source: Markus Heinsdorff)

Both being plant materials, bamboo and wood have similar properties, and can be used in either natural or processed form. Since engineered wood technologies are far more developed than bamboo processing, analyzing the development of timber can be seen as an inspiration for bamboo application (Huang 2019). Natural timber has an intricate fibrous layout and can be used for evolutionary optimized structures (Self and Vercruyssen 2017). However, it is hard to be applied to engineered structures because of its non-standardized material conditions and dimensional deviations during construction. Engineered timber has reliable product characteristics and is highly dimensionally stable. Nevertheless, its fibrous integrity is often lost and the standardization process requires effort and energy. For bamboo this is even more true: its natural hollow cylindrical geometry and high fibrous integrity constitute a highly optimized natural building material. Processing would compromise its structure, whereas its natural growth-dependent geometry deviations so far restrict many state-of-the-art construction processes.

1.2 Uncertainties of Natural Geometry and Deviation in Fabrication Process

Natural bamboo poles are historically highly dependent on manual operations in construction and difficult to combine with other standard building materials (Huang 2019). The main reasons are its material-related uncertainties, more specifically, its intrinsic geometrical variations. Bamboo rarely grows perfectly straight, the diameter of each pole is irregularly different.

The uncertainties of its natural geometry cannot be ignored, otherwise large deviations between desired- and fabricated structure will occur. Manual operations can also contribute to deviations. However, in most bamboo constructions, the deviations are manually corrected to reach relative, local accuracy.

It is of great importance to ensure global accuracy of fabricated structures, especially when they need to interface with other material groups. The success of integration requires tolerance of each material group to be within a specified range, e.g., the Chinese code GB/T 51233-2016 and GB 50755-2012 set the maximum error to ± 6.4 mm in length and ± 3.2 mm in width for prefabricated timber plates and ± 1 mm for steel components. Industrialized materials such as steel, concrete and engineered wood are used more frequently in construction because their geometrical and mechanical properties are more predictable (Lorenzo and Mimendi 2019). Although natural bamboo is a great candidate for building construction, more effort needs to be taken to control its tolerance.

1.3 Sensing System and Adaptive Fabrication Workflow

Digital fabrication processes firstly started from manufacturing industry for producing standardized products in assembly lines. Recently, digital fabrication has attracted great interest of the construction industry and opened up many possibilities. However, due to the fact that the design-to-fabrication workflow is usually unidirectional, such systems often can't react to unpredictable deviations.

In research, ideas are brought forward that deviate from static "digital chains". Behavioral and cyber-physical fabrication processes are defined by a set of adaptive rules and performative criteria (Brugnaro et al. 2016; Helm et al. 2017; Vercruyssen et al. 2018) and afford the ability to deal with uncertainties from the real world (Bruyninckx et al. 2001; Jeffers 2016; Vasey et al. 2014). In order to respond to the uncertainties, the fabrication system needs to be able to sense the as-built structure. An open design system is also necessary in order to react to the updated information (Crolla 2017) and allow adaptive adjustment to the next fabrication tasks (Bruyninckx et al. 2001).

Employing sensory feedback can help to build a more reactive fabrication process. A few researchers have already shown that vision-based sensing systems bring many new possibilities to digital fabrication. The project "Bamboo³" (Amtsberg and Raspall 2018) has employed vision sensing to get the individual bamboo section geometry in order to customize fittings for predefined joints. The project "Adaptive Part Variation" (Vasey et al. 2014) used vision feedback to make corrections on following elements in order to respond to the fabrication error of a cold bending steel rod structure. The project "Mesh Mould" from ETH (Dörfler 2018) used a vision-based sensing system to give a mobile robot more intelligence to adapt to the unpredictable material performance while welding steel rebars.

2 Research Aim

This research aims to develop an adaptive fabrication workflow for natural bamboo structures, which can compensate for cumulative deviations between the built- and the designed structure (Fig. 2), caused by material uncertainties. Such adaptation suggests an in-progress survey and the corresponding automated adjustment of the following fabrication tasks (Fig. 3), which are also responsible for varying levels of fabrication errors in other construction methods. With such an adaptive workflow, it is possible to efficiently build relatively precise bamboo structures. This opens up novel potentials for bamboo structures by enabling them to predictably interface with accuracy dependent building layers such as facades and roofs, and prefabricated construction elements made from materials such as glass and steel (Fig. 4).

Fig. 2. Deviation can be compensated rather than accumulated

Fig. 3. Cyber-physical information flow of adaptive fabrication process

Fig. 4. The accuracy of key control points of the structure enables predictable interfacing between accuracy dependent building layers

3 Methods

The adaptive workflow is composed of multiple iterations of adding bamboo elements onto the existing structure (Fig. 5). Each iteration begins by checking the computational design model, retrieving information about the connection areas and the designed pose (position and orientation) of the next element to be added. The respective connection areas within the built structure and the new bamboo element are both scanned with a depth camera. After estimating geometrical parameters from the sensory data and comparing them with the computational model, the pose of the next element is optimized for compensating the error that occurred in previous iterations. The geometries of related connectors are generated as well. According to that, CNC instructions for fabricating custom connectors and marking connection areas on the bamboo are generated and directly streamed to the fabrication agent. Finally, the bamboo element is assembled onto the existing structure.

The following three sections explain in detail the sensing and adaptation strategies, as well as the connection system used in this project.

Fig. 5. Fabrication workflow with in-process survey

3.1 Computer Vision

Setup. We use a comparably affordable Intel RealSense D415 as our sensor for initial tests. As an RGB-D camera, it provides color- and depth frames. The color image can be used for detecting objects of interest, and the depth information can be used for constructing 3D point clouds of these objects so that their poses and geometries can be measured. The performance of the sensor is tested with the depth quality tool provided by the RealSense SDK. The RMSE (root-mean-square error) of the depth value is around 0.36% in one meter, which is sufficient for initial tests.

In this project, the resolutions of color and depth image are set to 1920×1080 and 1280×720 respectively. For the 3D reconstruction, the factory-calibrated camera intrinsic parameters are used. During the scanning process (Fig. 6, Fig. 7), the camera is mounted on a tripod and an average of 20 frames of depth images are used to increase the precision of the depth data. A board with an asymmetric circle grid pattern is used for the alignment of the sensory data and the digital model.

Given the images, the task of the computer vision algorithm is to estimate cylinders representing certain parts of the bamboo poles. The cylinder is coded in seven parameters. They are given by a radius, a point on its axis, and a vector along the axis direction. Open source libraries OpenCV (Bradski 2000), Point Cloud Library (Rusu and Cousins 2011) and Ceres-Solver (Agarwal et al. 2018) are used in this project.

Fig. 6. Scanning bamboo pole

Fig. 7. Scanning built structure

Detection and Segmentation. One important step to extract useful information from the image is to segment it out of other irrelevant data. In our application, pixels of bamboo connection areas need to be segmented. We avoid using data of the whole pole since it leads to local inaccuracy when the pole is globally not straight.

The vision algorithm begins with detecting the circle grid pattern, which provides a reference coordinate system. The centers of those circles are detected by implementing the OpenCV function *findCirclesGrid*. With a known size of the pattern, the camera-to-pattern transformation is solved with the Perspective-n-Point algorithm using the OpenCV function *solvePNP*, with the mode *CV_ITERATIVE*.

Then all the pixels are iterated through and the corresponding 3D points in the reference coordinate system are calculated, so that it can be aligned with the digital model. The 3D point $\mathbf{p}$ is solved from the equation of the pinhole camera model:

$$d \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \mathbf{K} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \mathbf{T}_{co} \mathbf{p}, \quad (1)$$

where d is the depth value, u and v are the pixel coordinates, $\mathbf{K}$ signifies the camera calibration matrix, and $\mathbf{T}_{co}$ signifies the object-to-camera transformation matrix.

As the center line and radius of the cylinder segment is roughly known, the distance from the point to the cylinder is calculated and if it is below a specified threshold, it is classified as a point on the cylinder.

The following figures give examples of the results. The reference objects and the bamboo segments (marked purple) are correctly segmented (Fig. 8, Fig. 9) and aligned with the digital model in the 3D-modelling software Rhinoceros (Fig. 11, Fig. 12).

Fig. 8. Detection of bamboo pole

Fig. 9. Detection of built structure

Fig. 10. Detection of drilled holes

Fig. 11. Aligned point cloud of bamboo pole

Fig. 12. Aligned point cloud of built structure

Apart from that, since the connection system that we use requires drilling on the pole, the positions of holes also need to be sensed and compared with their design positions (Fig. 10). As the holes are small and therefore difficult to detect, we insert a bolt into each hole with its head painted black. A rectangular region of interest is set and those two black heads are detected using circle Hough Transform, which is also an implemented function in the OpenCV library. The two centers are used in the following adaptation process.

Least Squares Cylinder Fitting. After having the point clouds, we use least square method to fit a cylinder representing that bamboo segment into our data. The seven

cylinder parameters are given by minimizing the sum of the squared distance from all the points to the cylindrical surface:

$$r, \mathbf{p}, \mathbf{v} = \operatorname{argmin}_{r, \mathbf{p}, \mathbf{v}} \sum_{i=1}^n (r - D(\mathbf{p}_i, \mathbf{p}, \mathbf{v}))^2, \quad (2)$$

where r is the radius, $\mathbf{p}$ is the point on the cylinder axis, $\mathbf{v}$ is the vector along its axis, $\mathbf{p}_i$ is the i -th point from the point cloud, $D(\mathbf{p}_i, \mathbf{p}, \mathbf{v})$ signifies the distance function from $\mathbf{p}_i$ to the axis, which is formulated as:

$$D(\mathbf{p}_i, \mathbf{p}, \mathbf{v}) = \frac{|(\mathbf{p}_i - \mathbf{p}) \times \mathbf{v}|}{|\mathbf{v}|}. \quad (3)$$

The nonlinear least squares problem is solved using Ceres-Solver. Before that, random sample consensus (RANSAC) implemented by Point Cloud Library (PCL) is used for removing the outliers as well as providing an initial guess for the seven cylinder parameters.

3.2 Adaptation

After comparing the scan result with the design information, the deviation can be noticed. The pose of the next bamboo element should adapt to the current situation and compensate for the existing error. The concept to achieve that is to move the next bamboo pole to such a location, where it is able to connect with the existing deviated structure while keeping future connection areas as originally designed.

Figure 13 shows one scan result from our experiment, where $\mathbf{l}_1$ and $\mathbf{l}_2$ signify the cylinder axes (aligned with the design model) given by scan result of the next bamboo element, $\mathbf{l}_b$ signifies the cylinder axis given by scan result of the built structure, d_c signifies the desired distance between the center lines defined by the connection system, $\mathbf{h}_1$ and $\mathbf{h}_2$ signify the axes of drilled holes on the built structure. $\mathbf{P}_1$ and $\mathbf{P}_2$ are two target points that the center-line of the next bamboo pole should ideally pass through. $\mathbf{P}_1$ indicates the connection position with the built structure, which can be calculated once $\mathbf{h}_1$, $\mathbf{h}_2$, $\mathbf{l}_b$ and d_c are known, while $\mathbf{P}_2$ indicates the desired connection position with the future bamboo element, which is given by the original design. The number of target points doesn't need to be limited to two since there might be more than two connections on one pole and the end points of the pole might also be required to reach some specific position in space. When those objectives are conflicting with each other, they can be set to different weights to indicate the priorities.

The adaptation process is formulated again as an optimization problem:

$$T = \operatorname{argmin}_T \sum_{i=1}^n (w_i \cdot D(\mathbf{p}_i, T(\mathbf{l}_i)))^2, \quad (4)$$

where T signifies the transformation of every line $\mathbf{l}_i$ to its ideal state $\mathbf{l}_i'$, n signifies the number of target positions, w_i signifies the weight of the i -th target position and $D(\mathbf{p}, \mathbf{l})$ signifies the distance function from point to line, which is similar to (3).

The problem can be again solved with a least squares solver. However, as all the data are loaded in the Grasshopper3D plugin for Rhinoceros, we used its evolutionary

Fig. 13. Geometrical parameters of sensing results used in adaptation process

optimization tool Galapagos for convenience. The rotational part of the transformation is parameterized by axis-angle representation. Together with the translational part, six parameters are optimized with the evolutionary solver.

The result of adaptation provides all the information needed for generating the geometry of a tailor-made connector as well as the locations for drilling the pole.

3.3 Connection

There are many types of connections for natural bamboo structures (Fig. 14). They can be divided into two main groups: traditional and modern. Mortise-tenon joints and lashing joints belong to traditional connection group in conventional bamboo buildings and they are usually used in combination. Modern bamboo buildings have higher requirements on joints, and therefore, metal connectors such as bolting joints and steel member joints are more frequently used. Meanwhile, many other connection possibilities are investigated in recent studies. To name a few, these are CFRP (carbon fiber reinforced plastics/polymer) reinforced joints, wooden-clamp joints and 3D-printed joints (Hong et al. 2019).

Fig. 14. Bamboo connection types. (a) Lashing joint. Erber Research Center, Thailand, 2014 (Image Source: Chiangmai Life Construction/Create Up Co., Ltd. and Markus Roselieb); (b) Bolt joint. Bamboo Bridge, Indonesia, 2016 (Image Source: ASF-ID/Andrea Fitrianto); (c) Steel member joint. Bamboo Pavilion for Expo Shanghai, 2010 (Image Source: Markus Heinsdorff/Tong Ling Feng); (d) 3D-printed joint. Sombra Verde's 3D Printed Bamboo Structure, Singapore, 2018 (Image Source: Airlab @SUTD/Carlos Bañón)

As for this project, the design of connection is also constrained by the adaptive fabrication approach. First, the geometry of the connector should adapt to different angles and distances between two bamboo poles and their different diameters. Second, to enhance the performance of the joint and deploy the potentials of the system's precision, the poles should be held with a bending-stiff connection. For fabrication, this shifts the responsibility of accuracy to the advanced digital fabrication system, while the dexterity of human still is best suited to fasten the connectors.

Figure 15 shows the design of connectors which are used in the following experiments. All of them are 3D-printed with PLA filament, but have the potential to be fabricated out of wood by robotic milling to increase their performance and minimize fabrication time. The geometry is generated automatically by a custom grasshopper script with the parameters of two cylinders as inputs.

Fig. 15. 3D printed connector prototype

Fig. 16. Low-cost task-specific machine

Two holes need to be drilled on each bamboo pole to be assembled, which can also give indications to human during assembly process. The positions of the holes on the cylindrical surface can be calculated from the cylinder parameters and sent to the CNC machine or industrial robot for the drilling. For this project, we made a two-axis machine (Fig. 16), which is low-cost and specific to this task. A servo motor is used for rotating the bamboo pole into the desired orientation, while a stepper motor together with belt and pulley is used for moving a guiding block to the desired position along the axis of the pole. The precise turning of the bamboo pole and positioning of the guiding block makes it possible to manually drill at required locations. Both motors are controlled by an Arduino Uno microcontroller.

Other connection design options which can avoid drilling on the bamboo pole to keep its intrinsic fiber layout intact are under development, for example, a tailor-made clamping joint. However, without drilling, the connecting areas on the pole need to be properly indicated by other methods.

4 Experiments

4.1 Zigzag Structure

Setup. The first experiment is intended to validate the effectiveness of the above mentioned in-progress survey and adaptation methods. A simple zigzag geometry is chosen

as the building goal. It consists of five bamboo components with 30 cm length. The diameter of the pole is ranging from 18 to 22 mm. Two groups of raw bamboo poles are prepared. Both of them are used for building the same designed structure in the same sequence with three different methods: Method A (Fig. 5) is exactly the proposed workflow of this project as described in the method chapter, while Method B and C (Fig. 17) are used to provide references for the performance validation. Unlike Method A, in both Method B and C, in-progress survey is not performed and the measurement of the bamboo poles happens only once before all connectors are fabricated. While Method B employs vision-based techniques to scan the raw material once before assembly, in Method C, the poles are assumed to be straight and their diameters are measured with a caliper manually. The latter is what typically would happen in bamboo construction.

Fig. 17. Method B (pre-scan): material measured with vision-based sensing. Method C (manual measurement): material measured with a caliper. As comparison to proposed method of this project (Method A), both of them don't employ in-progress survey

Fig. 18. Raw material, joint nodes and assembled prototypes of group one

Fig. 19. Raw material, joint nodes and assembled prototypes of group two

Result. With two groups of material and three different methods, six zigzag structures are made and documented (Fig. 18, Fig. 19). All of them are again scanned and compared to their designed states. With all the methods, the results (Fig. 20, Fig. 21) showed noticeable deviation from their designed final state. The primary cause of the deviation is likely to be the limited accuracy of the used sensor and computer vision algorithm. However, the results of Method B and C show significantly larger deviation of the fourth and fifth bamboo pole. The center line of every pole is estimated again with the cylinder fitting method, and its position error (distance between midpoints) is plotted (Fig. 22, Fig. 23). In comparison to an overall accumulating trend of error with Method B and C, the errors of Method A fluctuate at a relatively low level as the building process

continues, which matches our expectation. A comparison between the results of Method B and C indicates that “pre-scan” helps to reduce the error in magnitude, but cannot prevent its accumulation.

Fig. 20. Result point clouds of group one. Three-dimensional deviation up to 65 mm

Fig. 21. Result point clouds of group two. Three-dimensional deviation up to 40 mm

Fig. 22. Position error of group one

Fig. 23. Position error of group two

4.2 Tree-like Structure

Setup. The second experiment is intended to apply the proposed method to achieve a more complex three-dimensional structure. As the top bamboo poles need to interface with prefabricated elements, high accuracy needs to be achieved. A tree-like structure (Fig. 24) is designed to reach the 4 target points in space. Since prefabricated elements typically are cut in size and drilled in advance, their positions impose a hard constraint on the natural bamboo assembly. After the bamboo structure is fabricated, customized pole-to-plate connectors are 3d-printed according to the final step of sensing. They can correct deviations up to 10.0 mm at the end of the poles.

Result. Figure 24 and 25 show the result of second demonstrator. The structure is 45 cm tall, cover a space of 26.0 cm × 26.5 cm. The average deviation of 4 final points is 8.26 mm according to the final survey. Through adapting the geometries of pole-to-plate connectors to those deviations, the interfacing is successful.

Fig. 24. Designed target points for interfacing with the prefabricated plate. Average deviation of 4 final points is 8.26 mm

Fig. 25. Finished structure. Successfully interfacing with plate through adapting the geometries of pole-to-plate connectors

5 Discussion

In conclusion, we have presented a feedback driven adaptive workflow for efficiently surveying and correcting deviations during the construction of natural bamboo structures. This is an important step towards reliable and predictable digital fabrication methods for large-scale bamboo architecture. The current study is limited by the accuracy of the sensor, detection algorithm, manual drilling and node valence. Still we show that tolerances can be significantly reduced even with low-cost sensors and equipment. Such approach can lead to predictable and semi-automated bamboo constructions, which is hardly achieved in other state-of-the-art bamboo fabrication workflows (cf. Crolla 2017; Amtsberg and Raspall 2018). The application of bamboo in construction can thus be expanded (Fig. 26). For instance, it may enable bamboo structures to interface with some prefabricated components made of wood, metal or glass, so that they can be used as building substructures for roofs and facades, or even be used on top of existing structures and fit them well. It may also enable the construction of bamboo structures in complex shapes (e.g., space frames) efficiently and reliably. To demonstrate the approach in full architectural scale, further development is necessary in areas of sensing hardware, digital feedback automation, and intuitive human-machine interfaces for on-site information visualization.

Fig. 26. Application scenarios of bamboo pole based structures integrated with conventional building materials. (a) Substructure of bridge; (b) Structure in multi-story construction; (c) Facade substructure; (d) Space frame

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