

Digital workflow for the accurate computation of the geometric properties of bamboo culms for structural applications

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Abstract. Bamboo is one of the most promising sustainable construction materials due to the large endemic natural reserves prevalent in the Southern Hemisphere. However, industrialised materials, such as concrete, steel and aluminium have overshadowed the application of natural bamboo culms, due to the high-quality assurance achieved over decades refining the production processes of structural elements manufactured from the former. As a result, the physical, geometric and mechanical properties of these industrialised structural elements are quantifiable, predictable and in agreement with international standards. This research presents the details of a digital workflow to quantify the inherent geometric variability of bamboo culms as part of a new quality assurance process for this natural structural element. This workflow relies on the use of a mid-range, commercially available structured-light 3D scanner to accurately capture a point cloud of the bamboo geometry and generate a corresponding polygon mesh. Digital models of three different bamboo species were validated through comparison with key physical measurements finding that the adoption of these digital models can significantly improve the accuracy and efficiency of manual methods due to the complex irregularities found in bamboo culms. This work demonstrates the benefits of adopting a non-destructive, reverse-engineering approach to quantify the geometric properties of bamboo compared to traditional tools and methods. Overall, this research shows the potential of digital technologies to support the adoption of this natural material allowing for the re-assessment of design workflows and providing an opportunity for bamboo to compete with industrialised materials.

1 Introduction

1.1 Natural geometry

Bamboo is one of the most promising sustainable construction materials due to the large endemic natural reserves prevalent in the Southern Hemisphere. In its natural state (round pole) bamboo has been mainly used for construction purposes. Processed bamboo (bamboo strips or fibres used for composites) has been traditionally used to fabricate a wide and ever-growing list of products like woven panels, home accessories and furniture, among others. However, industrialised materials, such as concrete, steel and aluminium have overshadowed the application of natural bamboo culms due to the high-quality assurance achieved over decades refining the production processes of structural elements manufactured from the former. As a result, the physical, geometric and mechanical properties of these elements are quantifiable, predictable and in

agreement with international building standards. The wood industry has also experienced a stronger development compared to bamboo. Despite wood being a natural material, the elements that are commonly used for construction purposes are cut down into uniform, prismatic and standard shapes and sizes (e.g. BS EN 336:2013). This approach helps to reduce the uncertainty of geometric properties and allows a more reliable use of the material.

Bamboo can be described as a long tapered hollow cylinder, with intermittent transverse membranes along its axis, known as “nodes”. From all the different species of bamboo, only some of them are regarded as suitable for structural purposes [1]. The internal biological composition of bamboo is well known [1,2], as well as its fast-growing properties [3]. Bamboo has proven to have a huge potential as a substitute for wood (and other industrialised materials) in a wide range of uses, one of which is in structural applications. Moreover, bamboo can be produced in rural areas,

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enhancing economic growth and reducing the ever-growing pressure over urbanisation [4].

This research presents the details of a digital workflow to quantify the inherent geometric variability of bamboo culms as a new quality assurance process for this natural structural element. For over five decades, studies on bamboo poles have focused on its mechanical, physical and biological properties, but there has been little focus on its geometrical variability, its significance on fabrication quality and its mechanical behaviour [5]. Janssen [6] compared a bamboo pole with similar industrialised structural elements, such as concrete or steel. He found that the main geometric variabilities on the geometry of bamboo were due to a) tapering, b) irregular internodal distances, c) variable cross sectional properties along its axis and d) out-of-straightness. As such, the accurate determination of geometric properties is fundamental to study the mechanical properties of round bamboo [7-11], behaviour of connections [12,13] and structural analysis [14,15] for which determining the pole's geometric variability is fundamental. Nevertheless, the only official international standard, ISO 22157-1-2004 [16], focused on the determination of the physical and mechanical properties of bamboo, is based on basic measurements of a limited and discrete number of properties that fail to capture the significant variation in the geometry of bamboo poles described by Janssen [6].

During the last two decades there have been studies that measured and analysed the variability of the geometric properties in bamboo poles. Amada et al [2] and Chung & Yu [7] performed similar studies to determine the variability of diameter, thickness and section properties (area and second moment of area) along the length of the bamboo, however they did not describe the measurement methodology adopted. A study by Ghavami & Moreira [5] focused on the influence of geometric imperfections, where they designed a non-destructive, mapping equipment to find the maximum initial imperfection of the element (out-of-straightness) as well as the cross-section variability along the culm. The geometric properties were used to calculate mechanical properties which resulted in good agreement when compared with mechanical tests. A simpler method was then designed by Richard [8] who also considered the effect of the out-of-straightness of the bamboo axis on its capacity. A more recent work on bamboo structures [17] also included the impact of the geometric effects on their study. ISO 22157-1-2004 [16] was used to measure the diameter and thickness in different sections of the culm, as well as the method described by Richard [8] to extract out-of-straightness. Additionally, a method to calculate the eccentricity for each cross-section was applied, defined as the deviation of a conic section from a perfect circle measured at both principal axes.

Due to the complexity of the aforementioned methods, a challenge remains to ensure the reliability and repeatability of the results obtained through

practical implementation, considering the significant variability of bamboo poles. Therefore, the importance of obtaining accurate and reliable measurements is undeniable. A study [18] pointed out that there are five aspects on which the geometric variability of bamboo has great impact: compression behaviour, flexural behaviour, grid-shells (or any 3D structure), visual grading and structural classification. However, manual measuring tools, adequate for most industrialised structural elements, are not necessarily the most suitable solution to address the challenge of accurately determining the geometric properties of bamboo poles. This research is therefore focused on adopting new non-contact, non-destructive, reverse-engineering technologies to overcome this challenge [19].

1.2 Bamboo digitisation

A 3D model that truly represents the natural shape of a bamboo pole can enable the study of the different geometric parameters of the pole, thus quantify its geometric variability. A three-dimensional (3D) model is a virtual representation of an object's geometry. The model can be manually built in a Computer-Aided Design (CAD) software if the geometry of the object is known. For "uniform", manufactured objects, the determination of their geometry is a straightforward process. Columns and beams in civil engineering or shafts and bearings in mechanical engineering are a good example of uniform objects. The virtual reconstruction of "non-uniform" natural objects however, is considerably more intricate and complex because of their more complicated irregular geometry.

For centuries, manual measurements have been the only way to acquire the geometry of objects, nevertheless, their accuracy has been questionable when applied on complex objects. Non-intrusive methods have been developed to acquire the geometry of objects [20], but only in the last two decades, with the emergence of digital technology, new imaging methods have been developed to acquire and build virtual models. The main methodologies involved the use of photographs [21,22], video-recording [23], laser sensors [24,25] and LED light projections [26,27].

Photogrammetry is a methodology that is normally used when the object can be represented by line-based structures, especially if the object has distinct texture. Laser and light scanner techniques are more useful when irregular objects like sculptures, reliefs or archaeological sites are involved [28]. More recently, it has been proved [29,30] that a combination of both methods can also be applied into large (e.g. buildings) and small (e.g. coins) objects to acquire both, high accuracy representations of non-uniform objects and their real colour.

This workflow relies on the use of a mid-range, commercially available structured-light 3D scanner [19] to accurately capture the bamboo geometry from which

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a point cloud model is generated. This point cloud is post-processed to be merged in to triangular polygons that compose the virtual surface of the bamboo. In contrast with other structural elements, bamboo poles are not suitable for geometric standardisation as each geometric parameter can display significant variability due to its nature [31]. Thus, the formal adoption of bamboo poles in structural applications requires this variability to be efficiently and accurately captured treating each individual pole as a ready-to-use structural element.

2 Materials and methodology

2.1 Material description

The geometric properties of bamboo poles will vary not only among species but also along single elements [31] and thus three different species from three different global locations were adopted for this study (Table 1). All bamboo poles were randomly selected to achieve a broad distribution of physical and geometric parameters (surface imperfections, curvature, nodal spacing, etc) to reflect the natural features of each specie.

2.2 Scan methodology

2.2.1 Scan subject

From a 3D scanning perspective, a bamboo pole can be described as a cylindrical slender element with a very small depth-to-span ratio. The internode surface is smooth and relatively shiny, with no distinctive texture or changes in geometry. The intermediate nodes along its length exhibit characteristic ridges and indentations (cut-off branch growths) with differing patterns and an increase in average diameter compared to the adjacent internodes. Oldhamii and Guadua bamboo presented similar straw colour, with shaded brown or light yellow small areas randomly sparse along the pole. Some Guadua presented small black irregular patches in random locations which are typical of the species. Moso bamboo had a dark olive colour due to the local treatment of carbonisation. The ends of all poles were cut at the internode to allow an unrestricted view of the pole wall and a portion of its inner surface.

2.2.2 Scan system

The equipment selected for the scanning system was an Artec Eva scanner [32] which is a hand-held device that operates based on structured light sensor technology [33]. Artec Eva has a resolution of up to 0.5 mm and a 3D point accuracy of 0.1 mm. The texture resolution is 1.3 mp and it supports 24 bpp of colour. It projects a white LED structure light using flash bulbs with a maximum frame rate of 16 fps and an exposure time per frame of 0.0002 s. The scanning range of the device is 0.4 to 1.0 m with a linear field of view of 214

x 148 mm to 536 x 371 mm (height x width) respectively. The scanner is able to acquire a maximum of 2 million points per second (point cloud).

The scanner was operated using a laptop Dell XPS 15 equipped with an Intel i7-6700HQ CPU @ 2.66 GHz, 16 GB of installed memory and a dedicated video card Nvidia GTX GeForce 960 m with 4 GB of memory. Processing of the point cloud was carried out using Artec's proprietary software Artec Studio 12 [32] in a work station Dell Precision with an Intel Xeon E5-1620v3 CPU @ 3.5 GHz, 32 GB of memory and a dedicated video card Nvidia Quadro K2200 with 4 GB of memory.

2.2.3 Scanner parameters configuration

The scanning process was configured specifically to optimise the acquisition of the bamboo geometry. The key parameters involved in the development of the process were: scanning time, file size and point cloud processing time. The parameters and the equations for the optimal geometry acquisition were obtained through experimental tests using the scanner, a range of bamboo sizes and variations of the set-up. The final optimal details, are described as follows.

The number of frames (F_n) acquired was crucial for the scanning process. This parameter depends on the scanning time (S_t) in seconds, and the acquisition rate expressed in frames per second (fps):

$$F_n = 120 + (S_t * fps) \quad (1)$$

$$S_t = \frac{L}{T_s} \quad (2)$$

$$T_s = 65 * rps \quad (3)$$

Where T_s is the translation speed of the bamboo along its length (mm/s), L is the total length of the pole (m), 65 is the translation in millimetres per rotation and 120 was the average number of frames required to acquire the inner bamboo surface at each end. The scan path consisted of simultaneous rotation and translation along the bamboo's axis, therefore, a minimum circumferential and longitudinal overlapping was needed. Figure 1 demonstrates the overlapping generated while scanning. The yellow frame (set of points) was the first shot taken by the scanner. As the pole simultaneously rotates and translates, the scanner will take a second shot, represented by the blue frame. The scanner continues taking shots until the pole rotates 360° and translates 0.065 m. This is considered a full cycle and is represented by the green frame. The helical scan will allow every frame to have both, a circumferential and a longitudinal overlapping. To geometrically ensure this, the translation speed will then depend on the revolutions per second (rps) that the bamboo is rotated at:

$$rps = \frac{fps}{F_r} \quad (4)$$

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Table 1. General description of materials

Bamboo Specie	Origin	No. of poles	Age (years)	Length (m)	Diameter (mm)	Treatment	Working site
Moso (<i>Phyllostachys Pubescens</i>)	Jiangsu, P.R. China	5	3 to 4	3.30	85	Carbonization/ Env. Chamber	Nanjing Forestry University, China
Oldhamii (<i>Bambusa Oldhamii</i>)	Veracruz, Mexico	10	3 to 5	5.00	65	Leaching/ Air-dried	UNAM, Mexico
Guadua (<i>Guadua Angustifolia</i> Kunth)	Valle del Cauca, Colombia	10	2 to 5	3.00	110	Leaching/ Air-dried	UCL, United Kingdom

Table 2. Scanning time and number of frames estimation

	Length (m)	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6
fps = 8 Ts= 17 mm/s	Scanning time (min)	0.5	1.0	1.4	1.9	2.4	2.9	3.4	3.8	4.3	4.8	5.3	5.8
	Frame Number	355	591	826	1061	1296	1532	1767	2002	2238	2473	2708	2944
fps= 4 Ts= 9 mm/s	Scanning time (min)	1.0	1.9	2.9	3.8	4.8	5.8	6.7	7.7	8.7	9.6	10.6	11.5
	Frame Number	342	564	787	1009	1231	1453	1676	1898	2120	2342	2564	2787

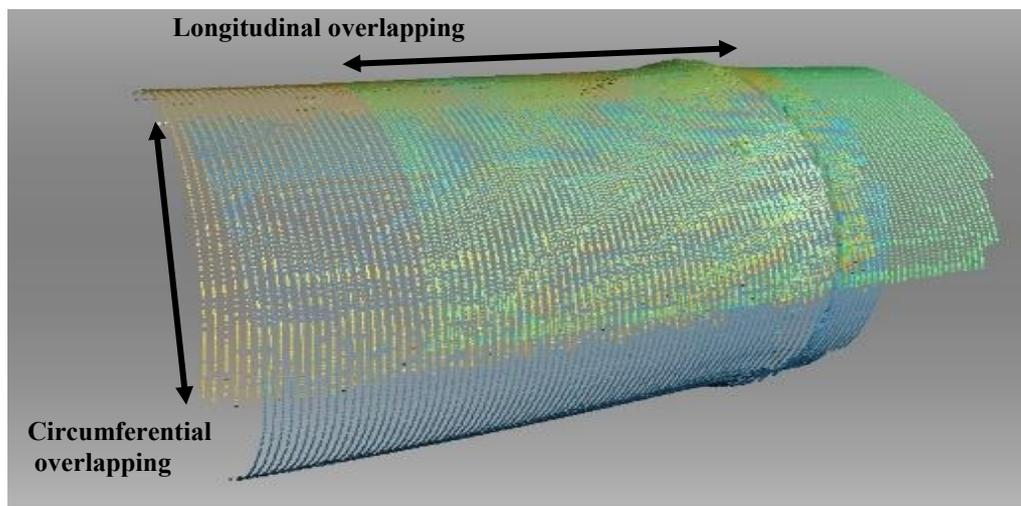


Figure 1. Circumferential and longitudinal overlapping

Where F_r is the number of frames needed per cycle of rotation. Through an iterative process the number of frames per rotation to efficiently scan poles of 60 mm to 150 mm diameter range was found to be 30 frames. Based on Equation 2, the scanning time (Table 2) was calculated for different lengths and translation speeds. File size and point cloud processing time also depends on the number of frames acquired. Figure 2 and 3 show the relationship of both parameters with frame number.

Figure 2 depicts a linear incremental relationship of file size as the frame number increases, however, in Figure 3, it is noticeable that the processing time of

point cloud increments exponentially with the number of frames. The size is directly related with file management operations (e.g. saving, copying, etc.), whereas the processing of the point cloud itself consists of the registration of the points acquired and generation of a mesh file.

In summary, the frame number was kept to the lowest possible value to optimise the total time of the

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scanning procedure. Table 3 shows the final configuration parameters of the adopted procedure.

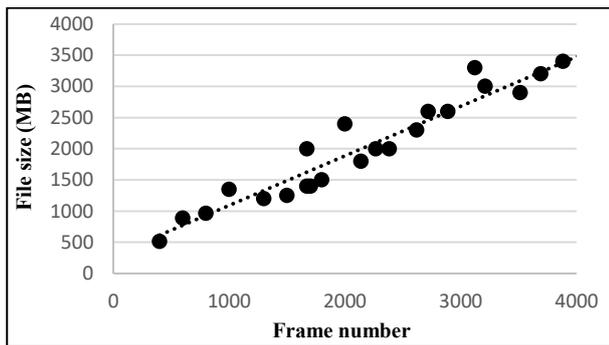


Figure 2. File size per number of frames

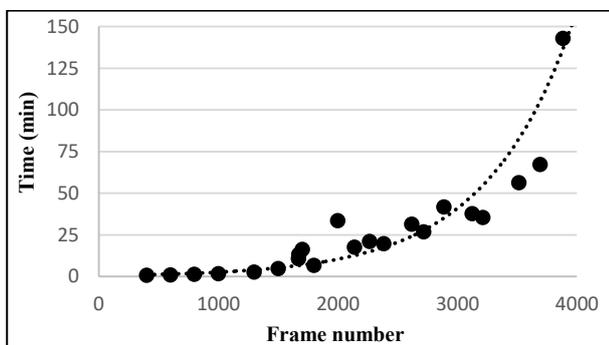


Figure 3. Point cloud processing time per number of frames

Table 3. Parameters adopted for scanning procedure

Geometry	Yes
Texture	Yes
Scanner-to-object distance (mm)	700
Field of view @700 mm (height x width - mm)	375x260
Frames per second (fps)	8
Maximum length of pole (m)	4
Maximum number of frames	2000
Maximum scan time (min)	4
Maximum File size (GB)	2
Maximum processing time (min)	10

2.2.4 Scanner set-up and process

The scanning set-up was developed considering simplicity and portability for on-site use. Scanner and bamboo motions were limited to reduce the effect of human factors during operation, which can affect the quality of the acquisition process. The workflow also considered that a single scan session was required to reduce noise and errors in the points acquired and therefore, increase the efficiency of the processing time [34]. The general set-up diagram is shown in Figure 4.

The scanning set-up consisted of four pipe stands, equipped with ball heads set at an angle of 120° (Figure 5), to support bamboo poles with diameter

between 60 mm and 150 mm at four equally spaced points along their length (Figure 4). The scanner was mounted on a camera dolly to follow a semi-circular path of 700 mm radius on a workbench (Figure 4). The height of the pipe stands at both ends was set 20 mm lower than the inner two, allowing a smooth translation as the bamboo pole moves along the supports.

Prior to scanning, two scanning target references were positioned at the bottom end of the pole and a single target at the top. These targets were used as a physical reference for the digital model and consisted of M5 socket head button screws inserted in predrilled holes so that their 7mm diameter hemispherical head is used as the scanned target (Figure 6). The position of these targets was within one diameter away from the end nodes.

The starting point of the scanning workflow is shown in Figure 4, with the scanner and bamboo positioned in a way that the bamboo bottom end and a portion of its inner surface were captured while the pole was rotated one full revolution around its axis. The scanner was subsequently slid 45° to the central position so that the bamboo could be scanned during a simultaneous rotational motion around its own axis and translation along its length. This motion creates a helical scan that must overlap throughout the entire bamboo surface acquisition (Figure 1). After the bamboo top end had reached the scanner central position, the scanner was slid 45° anticlockwise to repeat the process carried out at the beginning to capture the opposite end of the pole.

2.2.5 Scan registration and output

Point cloud processing was performed according to the methodology established on Artec Studio 12 [32] which consisted of several steps that would align and register the points, to ultimately generate a more readable 3D file, known as mesh .OBJ file [35]. Comparative analysis was carried out to define the values of these point cloud process parameters which are summarised in Table 4.

Table 4. Point cloud processing description

Point cloud process	Description
Fine Registration	Aligns captured frames within one session, considering geometry and texture acquired.
Global Registration	Converts local point coordinates, contained in the frames, to a global coordinate system.
Outliers removal	Removes small surfaces unconnected to the main surface.

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Fast Fusion Melts and solidifies the point cloud into a triangulated mesh.

Mesh Simplification Re-meshes the model, merging polygons.

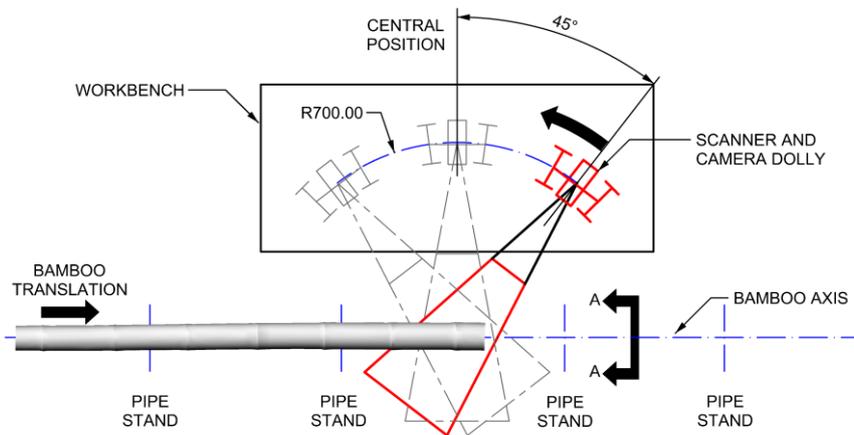


Figure 4. Bamboo scanning set-up

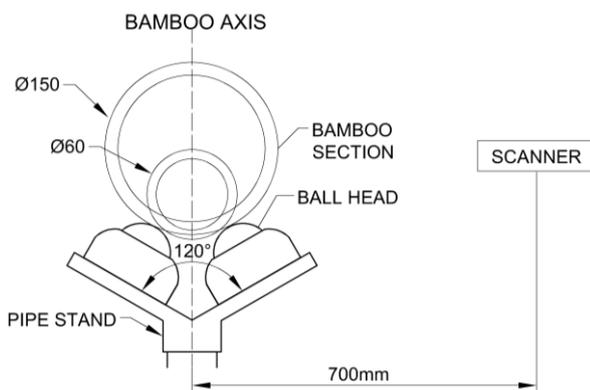


Figure 5. A-A section



Figure 6. Scanning target references

2.3 Digital and manual measurements

2.3.1 Digital measurements

Key measurements were obtained from the mesh model in order for them to be validated against the corresponding manual measurements extracted from the physical poles. Due to occlusions, the inner surface of the bamboo was just acquired at the ends, however, according to the literature [2,5,7,15] it has been found through the studies of different species (*Phyllostachys Edulis* Riv., *Bambusa Pervariabilis*, *Phyllostachys Pubescens*, *Dendrocalamus Giganteus*) that the wall thickness of bamboo tends to decrease linearly from bottom to top. Therefore, the portion of the inner surfaces were linearly extrapolated to generate an inner surface for each individual mesh file.

The diameter and thickness were extracted according to ISO 22157-1-2004 [16] which appoints that measurements are defined as the average of

measurements taken from each cross-section. Primarily, both outer and inner meshes were sectioned with a planar surface so that curves are fitted to the intersections (outer curve and inner curve). The area of each curve was then extracted, and the inner and outer equivalent diameters were calculated (Eq. 5a and 5b). An equivalent thickness was finally calculated as shown in Equation 6. Results of diameter and thickness were rounded to 1 mm and 0.1 mm following ISO 22157-1-2004 [16].

$$D_o = \sqrt{\frac{4 A_o}{\pi}} \quad (5a)$$

$$D_i = \sqrt{\frac{4 A_i}{\pi}} \quad (5b)$$

$$t_e = \frac{D_o - D_i}{2} \quad (6)$$

Where t_e is the equivalent thickness (mm) of the section and D_o and D_i are the outer and inner equivalent

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diameters (mm) calculated from the extracted outer and inner areas, A_o and A_i (mm^2) respectively. Areas and second moment of areas were then calculated from ISO 22157-1-2004 [16] (using D_o as the average diameter and t_e as the average thickness), and the values were rounded to 1 mm^2 and 1 mm^4 respectively. The length

of the pole was taken as the linear distance between two scanning reference points located at each end of the bamboo. The virtual reading was rounded to 10 mm, according to ISO 22157-1-2004 [16].

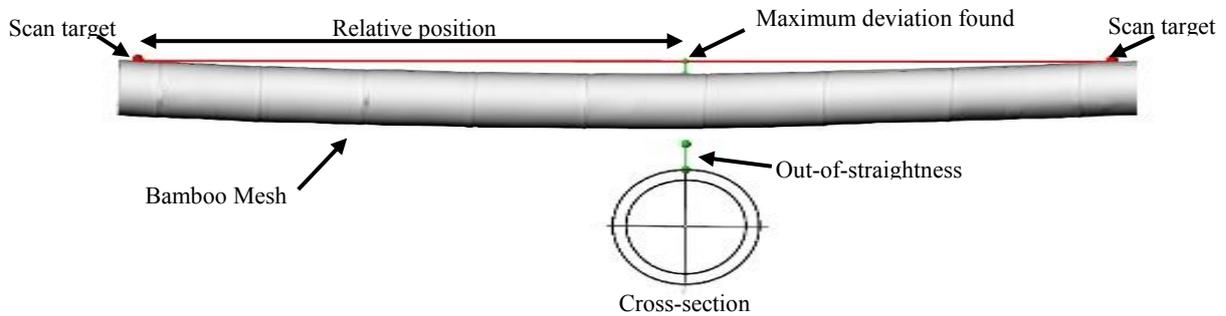


Figure 7. Virtual measurement of out-of-straightness

The out-of-straightness was measured from the virtual model as the deviation of the bamboo's surface from a straight line. As shown in Figure 7, the straight line was defined as a linear distance between two scanning reference points. The distance between the line and the surface was then evaluated along the line, until the maximum value was found. Out-of-straightness and relative position were recorded. The plane where the distance is measured passes through the axis of the bamboo (Figure 7). Out-of-straightness is not a measurement defined by ISO 22157-1-2004 [16], however readings were rounded to 0.1 mm.

2.3.2 Manual measurements

Manual measurements were taken from bamboo poles as a benchmark to compare against the results of the proposed digital workflow. These measurements followed the guidelines in ISO 22157-1-2004 [16] as shown in Figure 8 and were taken after cutting the bamboo at different sections along its length, rounded to 1 mm for diameter and 0.1 mm for thickness. Based on these measurements, average section properties were also calculated based on ISO 22157-1-2004 [16]:

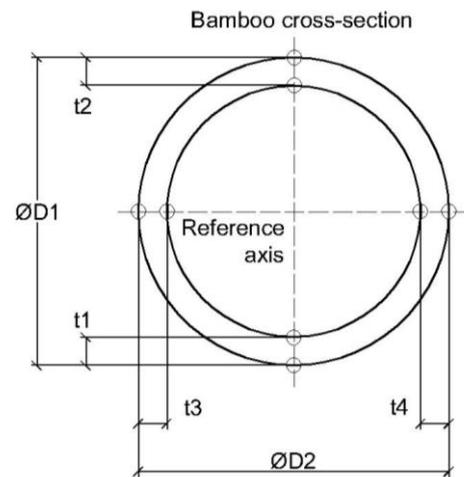


Figure 8. Measurements taken based on [36]

Cross sectional area:

$$A_c = \left[\frac{\pi}{4} \right] [D^2 - (D - 2t)^2] \quad (7)$$

Second moment of area:

$$I_c = \left[\frac{\pi}{64} \right] [D^4 - (D - 2t)^4] \quad (8)$$

Where D and t are the average diameter and thickness respectively measured in the cross-section shown in Figure 8. The total length was measured based on the scanning target references positioned at the bottom and top ends of the pole, consistent with the digital measurement. Readings were rounded to 10 mm, according to ISO 22157-1-2004 [16].

The out-of-straightness was also measured with the aid of the scanning target references. As this parameter is not described in ISO 22157-1-2004 [16], a similar procedure to that followed in the digital process was manually applied. A thread was tied from target to target and the distance between the thread and

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bamboo's surface was recorded at the relative position distance where the out-of-straightness was found to be maximum, according to the digital model (Figure 7). The recorded measurement was rounded to a tolerance of 0.1 mm.

3 Validation and discussion

The validation of the digital mesh model was carried out comparing its key dimensions against those in the real object. The results of the achieved accuracy of the

selected parameters for each bamboo specie are shown in Table 5.

The digital workflow was successfully applied in all 3 species, finding that the developed process allows the digitisation of a great range of diameters, bamboo colours and shapes that differed among the species selected. The duration of the workflow (scanning and post-processing) and file sizes were in agreement with those estimated in Table 3. Moreover, the calculated scan overlapping provided enough information to generate accurate models.

Table 5. Summary of results for the different geometric parameters

Geometric parameter	Total Samples	Accuracy (mm)	
		Average	Std. Dev.
Diameter	105	0.65	0.78
Thickness	105	0.43	0.43
Length	15	3.05	2.47
Out-of-straightness	15	0.50	0.57

Table 6. Accuracy results for the compared section properties

Geometric parameter	Total Samples	Average	Std. Dev.
Area	105	4%	2%
Second moment of area	105	3%	3%



Figure 9. Virtual model of Guadua bamboo

A total of 25 bamboos were manually and digitally measured, from which ten belonged to Oldhamii, ten to Guadua and five to Moso species. Including trials, a total of 500 additional linear meters of bamboo from three different species were scanned and processed showing the efficiency of the proposed workflow. These models form the basis of a wider database that allows further geometric analyses of the different imperfections in bamboo culms and therefore, consider these imperfections in their structural and mechanical behaviour (Figure 9).

As shown in Table 5, diameter and thickness (which were measured together on the same section) had a similar average accuracy of 0.65 mm and 0.43

mm respectively. These values were in accordance with the scanner specifications, indicating that the bamboo section extracted from the mesh model represented the true surface with a high level of accuracy. The average accuracy for the pole length was 3.05 mm over a total average length of 3.5 m which is considered a very good index of accuracy when compared with the standard tolerances for shapes and sizes applied to wood. According to BS EN 336:2013 [37] an allowance of -3 to 5 mm of tolerance is accepted on dimensions over 300 mm.

One of the most important parameters that can be accurately extracted using the bamboo virtual model obtained from the scanning methodology is the out-of-

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straightness. As Ghavami & Moreira [5] pointed out, the out-of-straightness is a deviation on bamboo's main axis that diminish the loading capacity of the element in conjunction with negative effects in stresses and deformations. Previous methods to measure this parameter [5,8] have demonstrated to have good agreement with experimental tests, however, the manual methods proposed would be difficult to implement due to their complexity and time-consuming nature. The average accuracy obtained for this parameter was 0.5 mm which increases the level of confidence in the digital methodology applied. The digital method to calculate the maximum out-of-straightness for each pole demonstrated that even the most complex dimensions can be easily extracted, and even automated, to obtain high accuracy results. When measuring the out-of-straightness by hand however, the task was complicated and time consuming, diminishing the confidence in the method applied.

In addition to the manual measurements, the section properties of the real and virtual models were also compared (Table 6). The average value for area and second moment of area were 4% and 3% respectively. Both parameters were calculated based on the average diameter and thickness of each section, and therefore, these results confirm the accuracy of results obtained in the validation of dimensions.

In summary, dimensional parameters and cross section properties showed a good agreement between the digital model and the physical pole. As explained previously, reliability and repeatability of the manual measurements are always compromised when applied to irregular objects, hence, a more systematic method should be applied to meet the quality assurance requirements in the building industry. The workflow presented in this research shows a remarkable improvement in bamboo geometry acquisition, it considerably reduces the measuring-process time and diminishes uncertainties on the results. Moreover, it allows the user to have a better understanding of the geometric variability and its implications in the project where the scanned poles are to be used.

4 Conclusion

This research presents the details of a digital workflow to quantify the inherent geometric variability of bamboo poles that can form part of a new quality assurance process for this natural structural element. This workflow relies on the use of a mid-range, commercially available structured-light 3D scanner to generate a polygon mesh model of the poles.

During the development of the methodology, the key parameters and scanning methodology were analysed and discussed to optimise the process both in terms of accuracy and efficiency. The driving parameter for the scanning process was found to be the total number of frames captured during the scan session, as the file size and point cloud processing time

are directly dependent on it. The methodology was also designed to ensure that each pole is captured in a single scan to add to the efficiency of the process.

To validate the model, manual and digital measurements were taken from 25 bamboo culms of three different species. Hand measure methods have been developed for years, yet there are different factors that can still affect the final accuracy, however, the workflow presented in this research shows a remarkable improvement in bamboo geometry acquisition, reduction of the measuring-process time and diminishment of uncertainties in the measurements recorded. An overall accuracy under 1mm was verified for diameter, thickness, and out-of-straightness. For the overall length, an average accuracy of 0.87 mm/m was achieved. The process developed in this work is therefore considered as an accurate 3D workflow to reverse engineer bamboo culms, as the overall validated accuracies are well below the 10mm accuracy threshold suggested for prototyping or reverse engineering applications [38].

This work demonstrates the benefits of adopting a non-destructive, reverse-engineering approach to quantify the geometric properties of bamboo compared to traditional tools and methods. Overall, this research shows the potential of digital technologies to support the adoption of this natural material allowing for the re-assessment of traditional design workflows and providing an opportunity for natural bamboo culms to compete with industrialised materials.

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