Automating Surface Flatness Control using Terrestrial Laser Scanning and Building Information Models

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Abstract

Current practice in the control surface flatness requires a significant amount of time and labour, and delivers results based on few sample measurements. Developments of Terrestrial Laser Scanning (TLS) and Building Information Modelling (BIM) offer great opportunities to achieve a leap forward in the efficiency and completeness of dimensional control operations. This paper presents an approach that demonstrates the value of this integration for surface flatness control. The approach employs the Scan-vs-BIM principle of Bosché and Haas (2008) [1] to segment TLS point clouds acquired on-site, by matching each point to the corresponding object in the BIM model. The novel approach then automatically applies two different standard flatness control techniques, Straightedge and F-Numbers, to the TLS points associated to each floor, and concludes with regard to their compliance with given tolerances. The approach is tested and validated using data from two actual concrete slabs. Results confirm the suitability of using TLS for conducting standard dimensional controls, and validate the performance of our system when compared to traditional measurements methods (in terms of both quality and efficiency). Furthermore, a novel straightedge generation method is proposed and demonstrated that enables more complete and homogeneous analysis of floor flatness for insignificant additional processing times.

Keywords: laser scanning, BIM, quality control, surface, slab, flatness, regularity

1. Introduction

Methods and measurement tools for dimensional quality control in the construction industry have evolved significantly in the recent time. While traditional tools like tapes, plumb bobs and gauges are still widely used, more advanced laser-based technologies are now also available that include hand-held laser distance measurers and total stations. These new measurement technologies make single measurements with significantly better accuracy and precision. However, their utilisation remains labour and time-intensive [2, 3, 4], and as a result their use must rely (heavily) on sampling techniques. For example, the measurement of wall verticality using total stations is conducted by measuring only a few points at different heights along horizontally (sparsely) -spaced vertical lines. Similarly, the measurement of warehouse floor slabs with defined-movement areas is conducted by measuring the vertical deviation from the horizontal plane at discrete points along the manually identified centre lines of the lifting equipment's wheel paths [5] – as opposed to the entire width of the wheels or even the entire width of the equipment path. The risk with such partial measurements is that locations presenting discrepancies larger than specified can remain undetected, leading surveyors to wrong conclusions with potentially detrimental consequences [3, 6]. Furthermore, it can be argued that the significant involvement of humans in the process adds the risk of manual errors [2, 3, 4, 6]. There is thus a need for approaches that enable more complete (*i.e.* dense) and reliable dimensional measurement, without requiring disproportionate amounts of human interaction and time.

Terrestrial Laser Scanning (TLS) and Building Information Modelling (BIM) are increasingly used in the Architectural, Engineering, Construction and Facilities Management industry (AEC&FM) due to the significant performance improvements that they can support. In the UK, they have been identified as two of the main industry innovations with significant potential to help it achieve a 15%-25% reduction in capital project costs [7].

TLS is a modern technology that is revolutionizing surveying works. As highlighted in numerous previous research works (*e.g.* [2, 3, 4, 6]), TLS can provide surveyors with the means to conduct far more complete (dense) measurements in relatively short times, which would in turn lead to more

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reliable dimensional control results. However, its use in practice remains limited essentially because of some concerns regarding level of measurement accuracy it provides, and the time required to manually process the data to extract the dimensions of interest.

This paper presents a novel approach that integrates TLS and BIM to significantly automate the processing of TLS data, and hence the overall control process. The system automatically (1) identifies the TLS data corresponding to each floor in the 3D model, and (2) applies control procedures. The approach is demonstrated here in the case of surface regularity/flatness quality control, with the application of the two common standard flatness control procedures, the Straightedge and F-Numbers methods. The approach achieves results that compare favourably with those obtained using traditional measurement techniques. Furthermore, a novel variation of the straightedge measurement technique is presented that enables more complete flatness controls with negligible additional processing time.

The rest of this paper is organized as follows. Section 2 first reviews existing methods for conducting floor regularity control, and then analyses how the integration of TLS and BIM can enable a leap forward in the efficiency and completeness of dimensional control operations. The proposed approach and implemented system are then presented in Sections 3 to 6. Results of the experiments conducted to test and validate the proposed system are reported and analysed in Sections 7 and 8. Conclusions are finally drawn and recommendations for future work made in Section 9.

2. Background

2.1. Surface Flatness Quality/Compliance Control

Surface flatness, or surface regularity, is *"the deviation in height of the surface* [...] *over short distances in a local area"* [8]. The control of surface regularity can be done using different methods, such as: the Straightedge method [8, 9], the F-Numbers method [9, 10], the TR34 method [5] and the Waviness Index method [11]. In the following, we focus on the two most common and as well as differing ones:

- The **Straightedge method** [8, 12, 13, 9] that is traditionally and commonly used; and
- The **F-Numbers method** [9, 10, 14] that is mathematically more complex, but more complete and somewhat easier to implement.

2.1.1. Straightedge Method

In the Straightedge method, the surveyor lays a straightedge at different locations on the surface and measures the maximum deviation under it, preferably using a stainless steel slip gauge [8]. The deviation is then compared to a tolerance to validate or reject the level of flatness of the surface. A long straightedge (2m in Europe, 3m in the USA) is used to control *global* flatness, while a smaller ruler (0.2m in Europe, 0.3m in the USA) can be used to control *local* flatness.[1] Control of global flatness enables the discovery of larger deformations, like bending; while local flatness is measured to identify little gaps or bumps on the slab.

In the UK, standard tolerances when controlling flatness in concrete structures using the Straightedge method are provided in BS EN 13670 [12] (UK implementation of the European Standard EN 13670) that specifies global and local flatness tolerances for 'moulded or smoothed surfaces', and 'not moulded surfaces' (see Table 1). In [13], CONSTRUCT publishes different tolerances (see Table 1). While complying with BS EN 13670, these tolerances are more specific, referring to four different standard types of surfaces – formed and unformed surfaces, and with basic, ordinary or plain finishes (see Table 1).

The specifications provided in [12, 13] are not specific to floor surfaces. In contrast, the multi-part standard BS 8204 [8] provides tolerances specifically for the surface regularity of direct finished base slabs or levelling screeds (see Table 1). It is notable that these tolerances are only for global flatness (*i.e.* deviation under a 2m straightedge); local flatness is surprisingly not considered. Furthermore, this standard does not refer to the same types of finishes as [12] or [13]. Instead, three different levels of standard are defined: SR1, SR2 and SR3, with SR1 the highest standard.

In the USA, tolerances for concrete slab flatness are provided in ACI 117 [10]. Similarly to BS 8204, ACI 117 provides tolerances for 100% compliance – *i.e.* 100% of the straightedge deviations measurements must be below the given tolerance. However, in contrast with BS 8204, it also requires a second set of tighter tolerances be defined for 90% compliance – *i.e.* 90% of the straightedge measurements must be within the given toler-

[1] Note that the words flatness and levelness are not used consistently within standards and the literature. In some sources, *e.g.* [8, 12, 13, 15], *levelness* refers to the departure from the designed level, and thus does not relate to surface regularity; while in other sources, *e.g.* [5, 10, 9, 14], it is used in reference to the *global flatness* (while the word flatness relates to the local flatness). In this paper, the former nomenclature is used.

ance [16] (see Table 1).

Source	Surface/Floor classification		Tolerance (mm) Global	Local
BS EN 13670 [12]				
	Not-Moulded surface		15	6
	Moulded or smoothed surface		9	4
CONSTRUCT [13]				
	Basic unformed surface		12	5
	Ordinary unformed surface		9	3
	Ordinary surface		9	5
	Plain surface		9	3
BS-8204 [8]				
	SR3		10	n/a
	SR2		5	n/a
	SR1		3	n/a
ACI 117 [10]				
	Conventional	(100%)	19	n/a
		(90%)	13	n/a
	Moderately flat	(100%)	16	n/a
		(90%)	10	n/a
	Flat	(100%)	10	n/a
		(90%)	6	n/a

Table 1: Deviation tolerances for concrete surfaces as defined in BS EN 13670 [12] and CONSTRUCT [13], and specifically for floors in BS 8204 [8] and ACI 117 [10]. *Global* flatness is measured with a 2.0m straightedge (3.0m in [10]); *Local* flatness with a 0.2m ruler (0.3m in [10]).

Surprisingly, none of the British standards above specifies where the straightedge should be positioned on a given surface. A note in BS 8204 [8] only mentions that *"the number of measurements required to check levels and surface regularity should be agreed between the parties concerned bearing in mind the standard required and the likely time and costs involved."*

In the USA, ACI 117 [10] suggests that straightedges should be placed randomly on the surface. It further specifies that at least one sample must be taken for every 100 ft^2 of floor area and that samples must be taken parallel, perpendicular, or at a 45° angle to the longest construction joint of the test area. It is however acknowledged that *"there is no nationally accepted procedure for taking measurements or for establishing compliance of a test surface with this tolerance approach"* [10].

In France, the standard NF P11-213 [17] – standard for design and construction of concrete floors – recommends that a minimum of 10 measurements should be conducted for each slab, but does not provide any further information as to where those measurements should be conducted. The only relevant information on this aspect was found in the CSTB "Avis technique 20/10-193*V1" [18] that suggests the use of a square grid of lines spaced by 1m.

It is widely agreed that the Straightedge method is simple to understand, inexpensive and thus still widely used. However, it presents important deficiencies including:

- The difficulty in testing large areas of floors;
- The difficulty of randomly sampling floors; and
- The inability to reproduce testing results.

For these reasons, alternative approaches for floor profiling have emerged that are simpler and make use of modern measuring technologies, in particular the F-Numbers method.

2.1.2. F-Numbers Method

ACI 117 [10] argues that the F-numbers method provides a *"convenient means for specifying* [and controlling] *the local floor profile in statistical terms"*. The F-Numbers method summarizes a floor profile with two numbers:

- $\mathbf{F_F}$: A statistically calculated number that takes into account the mean and standard deviations of sample measurements of 12in (∼0.3m) incremental curvatures. F_F thus estimates the floor's global flatness; and
- $\mathbf{F_L}$: A statistically calculated number that takes into account the mean and standard deviations of sample measurements of 120in (∼3m) elevation differences. F_L thus estimates the floor's levelness.

The higher the F_F and F_L numbers, the flatter the slab. ACI 302 [9] and ACI 117 [10] note that, for random-traffic floors, two sets of F_F/F_L tolerances should be provided: one for the overall floor flatness, and one for the flatness of individual local floor sections – *i.e.* portions of the floors bounded by columns, walls and joints. Minimum local values are generally set at 67% of the specified overall values [9]. In ACI 117 [10], tolerances are provided for four different standard floor classes (see Table 2).

The F-Numbers measurement method is described in detail in ASTM E 1155-96 [14]. It consists in defining a grid of sampling lines (separated by at least 1m) on the surface of each floor section, measuring point elevation at regular 0.3m (12in.) intervals along each line, and finally calculating the F_F

Floor Classification	Tolerances (F_F/F_L) Overall	Local
Bull-floated	15/13	13/10
Conventional	20/15	15/10
Flat	30/20	15/10
Super Flat	50/30	25/15

Table 2: F-Number tolerances for concrete slabs for random-traffic floors [10, 5].

and F_L values for each floor section and subsequently for the entire floor. Instruments that are most adequate to conduct the required measurements include optical levels, total stations, inclinometers or longitudinal differential floor profilometers [14].

While there is no direct relationship between F-Numbers and straightedge millimeter deviations, some rough equivalences have been suggested between the gap under the 10ft (3m) straightedge and F_F, as summarized in Table 3 [10]. Note that the Straightedge method does not require that straightedges be levelled, and thus cannot provide information on the floor's levelness, and be in any way compared with F_L.

F_F	Gap (mm)
12	13
20	8
25	6
32	5
50	3

Table 3: Rough equivalences between F_F and gaps under a 10-ft straightedge [10].

Terrestrial Laser Scanning (TLS) and Building Information Modelling (BIM) are increasingly used in the Architectural, Engineering, Construction and Facilities Management industry (AEC&FM) due to the significant performance improvements that they can support. Their value with regard to construction quality/compliance control is reviewed in the following sections.

2.2. Terrestrial Laser Scanning (TLS) for Quality/Compliance Control

Terrestrial Laser Scanning (TLS) is a novel technology that is revolutionizing surveying works. A laser scanner sweeps its entire surrounding space with laser light to acquire 3D data points with good accuracy, high density, and great speed. For example, the scanner used for the experiments reported later can save points between 0.6m to 120m with a speed of up to 976,000 points per second, producing a full scan of 10 million points in a matter of minutes, with a range measurement systematic error of ±2mm at 10m and 25m, and a random error between 0.5mm and 2mm at 10m and 25m [19] — it must be recognized these errors are indicative values that can vary significantly depending on the scanning context (material, scanning angle, *etc*).

Point clouds provided by 3D laser scanners can be used directly for measurement and visualization, but can also be post-processed to extract underlying valuable information. Two important applications of TLS are as-built/as-is modelling [20, 21, 22, 23] and construction quality control [2, 3, 24, 6].

The potential of TLS for quality control has long been recognized [2], and many researchers have developed approaches to compute and display the deviations of laser scanned points with reference surfaces for visual inspection of surfaces [3, 4, 25, 26]. However, these works focused on visualisation and did not consider the issue of detecting and characterizing defects.

Akinci et al. [3] proposed a first formalization for integrating project 3D models and sensor systems (in particular TLS) for construction quality control, *i.e.* defect detection and characterization. Bosché et al. [4] then presented a first implementation of such a system. The method uses what the authors later called the *Scan-vs-BIM* principle [27], where the TLS data is registered (*i.e.* aligned) in the coordinate system of the project 3D BIM model. This enables the system to automatically match TLS 3D data points to each BIM model object; and infer the recognition of those objects. In [4], the authors then demonstrate an approach for automatically characterizing positional deviations (*i.e.* deviations equivalent to rigid transformations, such as out-of-plumb deviations of columns) by applying a local fine registration of the BIM model objects to the matched TLS data points. This approach cannot however assess local shape and surface irregularities (*i.e.* deviations equivalent to non-rigid local deformations, such as floor flatness).

Regarding the assessment of surface regularity, Tang et al. [6, 28] have explored three algorithms for detecting and characterizing surface flatness deviation from TLS point clouds. Their main algorithm works in 3 stages: (1) Apply Gaussian noise filtering to the point cloud; (2) Fit a plane against the overall point cloud; and (3) Calculate the distance between each point and the overall plane. Two other varying algorithms are also considered. In the second algorithm, noise filtering is not applied at the beginning of the process but to the map of distances of the points to the overall plane. In the third algorithm, a variation of step (3) is considered where, instead of directly calculating the distance of each point to the overall plane (an approach sensitive to noise), a sliding window is used to calculate a plane approximating the local surface at each point. The centre of the local plane is then used to calculate the deviation to the overall plane. Each window position produces a single measurement of deviation from the global reference plane, and all deviations are combined to form the deviation image and estimate the overall slab deviation. While the third algorithm is theoretically less sensitive to noise, Tang et al. report that in their experiments the first two algorithms actually achieved the best results.

In contrast with existing surveying technologies, TLS provides dense measurements for entire surfaces. The methods proposed by Tang et al. [6, 28] take advantage of this and measure deviations over the entire surface – a significant advantage over the traditional F-Number and Straightedge methods that only conduct sparse sample measurements. However, despite a detailed analysis of their performance, the methods presented by Tang et al. characterize defects using metrics that are incompatible with current standards. As a result, it is difficult to assess the performance of their approaches for surface flatness control. In fact, to the knowledge of the authors, no work has been reported to date on the suitability of employing laser scanning for slab flatness control, and how it compares with existing methods.

2.3. BIM for Construction Quality/Compliance Control

BIM is an intelligent digital model -based process for creating and managing building and infrastructure projects more efficiently, economically and sustainably. It is a process change that is driven by significant technological innovations, at the heart of which is a semantically-rich and collaboratively generated and managed digital 3D BIM model [29].

The value of BIM models with regard to specifications and compliance control is at two levels. First, the integration of specifications within BIM models would enable reliable and efficient issue and management of construction project specifications. *NBS Create* [30], released by NBS in 2013, is a software tool that enables just that: the automated identification and management of the standards and specifications relevant to all components present within a given BIM model. The user then simply needs to specify the requirements identified by the system. Taking the example of an on-grade concrete floor, NBS Create can automatically link the relevant standards (*e.g.* BS 8204) and specifications (*e.g.* straightedge or F-Number tolerances), and the user then simply needs to detail the required tolerances. Since BIM models are aimed at being collaboratively managed and shared among all participants, such integrated models would give contractors and surveyors access to all specifications relevant to the different project components in a unique location, and in standard digital format.

Secondly, design BIM models (with integrated specifications) can support more efficient and robust construction quality/compliance control. Boukamp and Akinci [24] presented an approach that uses a project 4D BIM model with integrated specifications and automatically generates for the surveyor the list of building components to be controlled along with the related specifications based on the current construction progress. Their vision further included (a) the automated generation of detailed survey plans given those requirements and the available survey equipment; (b) the automated identification of deviations by comparison of the design BIM model and as-built data captured by the survey equipment; and (c) the automated identification of defects by comparison of the deviations with the defined specifications. However, no approach was proposed and demonstrated for those latter stages.

As reviewed in Section 2.2, a first automated approach for the stage (b) of this vision is presented and demonstrated by Bosché et al. [4], and uses the design project BIM model as prior information for the processing of TLS data for dimensional quality control. However, this approach does not support the detection and characterization of local surface defects, such as floor irregularity.

3. Contribution and System Overview

The Straightedge method for floor flatness control is simple, but weak and laborious. The F-Numbers method is more robust and can be implemented more efficiently using dedicated modern tools. However, the two methods remain labour and time-consuming and only provide a localized, partial analysis of surface flatness.

TLS and BIM models (augmented with specifications) offer great opportunities with regard to construction quality/compliance control, including for floor flatness control [24]. However, TLS data processing methods investigated to date either do not attempt to characterize surface deviations and thus detect defects in surface regularity [4], or focus on the performance of

TLS for single point deviation detection as opposed to overall floor regularity characterization [6]. Furthermore, none of these works has attempted to validate the use of laser scanning for floor regularity assessment by comparing it with current approaches.

In this paper, an approach is proposed that integrates TLS and BIM models and automatically characterizes floor flatness. The system assumes as input a BIM model augmented with specifications and a set of TLS scans acquired on site. It then uses the *Scan-vs-BIM* method of [31, 27] to align the TLS scans in the coordinate system of the BIM model, and match all TLS cloud points to the different BIM model components. Finally, it automatically applies the Straightedge or F-Numbers methods to control the compliance of floors. The diagram in Figure 1 summarizes this process. The advantages of this overall approach are:

Integration/Automation: the process is almost entirely automated; the only step potentially requiring user input is the alignment of the TLS scans with the BIM model. Data processing is thus conducted very rapidly. Furthermore, the results can be automatically linked to the BIM model, so that they can be easily shared with and reviewed by other project stakeholders.

Compatibility with current standards: the system applies current standard methods for floor flatness specification and control, and is thus entirely compatible with them. An improvement of the Straightedge method is nonetheless proposed that takes advantage of the density of data available, and provides a more complete picture of the flatness of any given floor.

The proposed approach was implemented in a software system and tested using real-life data from two concrete slabs. Results using the Straightedge method were particularly compared against those achieved manually.

Section 4 quickly reviews the Scan-vs-BIM system used at the beginning of the process. Sections 5 and 6 then describe the developed implementations of the Straightedge and F-Numbers methods, respectively.

4. Scan-vs-BIM system

The input of the proposed dimensional quality control system includes a 3D BIM model and a 3D point cloud (composed of one or more laser scans). The first step of the process consists in registering the point cloud in the coordinate system of the model (*i.e.* aligning the point cloud with the model). For this, we use the approach in [32] based on plane matches, but

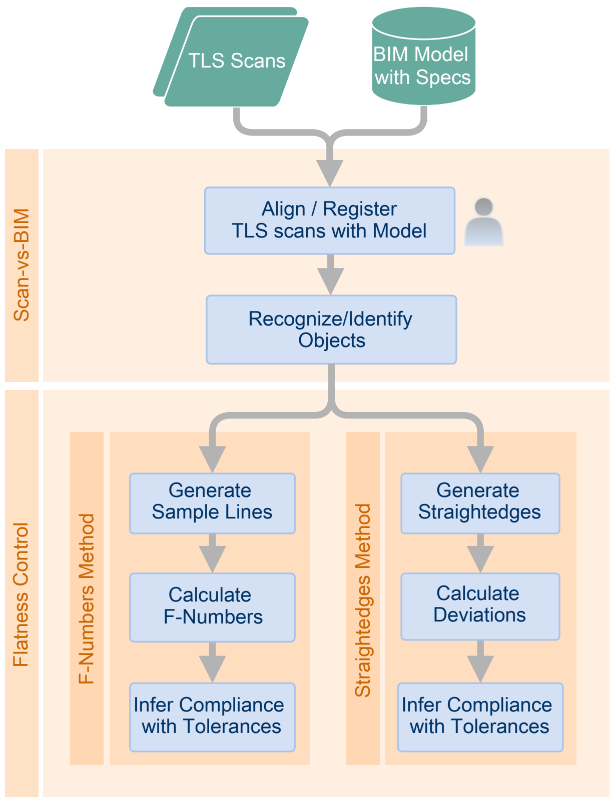


Figure 1: The process followed in the proposed approach and implemented system for floor flatness compliance control given a set of TLS scans acquired on site and the project 3D BIM model.

other approaches can be used (see [32] for a review). Then, each point of the point cloud is matched to a BIM model object (or none) using a metric combining two criteria:

(1) *proximity*: orthogonal distance of the point on the BIM model object surfaces; and

(2) *surface normal similarity*: similarity in orientation of the normals of the local surfaces around the TLS point and around its matched point in the BIM model — the matched point is the closest orthogonal projection of the TLS point on the BIM model objects.

This step essentially achieves a full segmentation of the initial point clouds in a set of sub- point clouds matched to the different BIM model objects. Then, the recognition of each object is inferred by comparing the surface covered by the set of matching points with the expected covered surface.

Upon the completion of this process, the user can select any object (*e.g.* a floor) and visualize the points associated to it, *e.g.* colour-coded according to their deviations from the surface of the object. Figure 11, later in this article, illustrates this Scan-vs-BIM process.

The performance of this process has already been demonstrated in [1, 31, 27]; it has been shown to work particularly well for structural components (that include slabs). We direct the reader to [1, 31, 27] for a detailed presentation of the approach and its performance. We also refer the reader to the work of Kim et al. [33] who present a similar approach.

5. Automated Straightedge Method for Flatness Control

We have digitally encoded the Straightedge method for floor flatness control, so that it can be applied to most floors. In our implementation, the control procedure is divided in three steps:

1. **Data pre-processing:** The input to this stage is the geometry of the floor and the point cloud associated to it. We assume that the floor's geometry is expressed as a triangular mesh, a common representation that can be automatically generated from 3D object representations used by CAD/BIM systems. The first pre-processing step identifies the points that lay on the floor's top face. The second step organizes those points in an array structure enabling efficient, directed point search.

2. **Generate Straightedges:** The input to this stage is the geometry of the floor's top face and the point cloud associated to it (organized in the array structure). The process consists in generating valid straightedges of specified length by searching for appropriately spaced pairs of points in the point cloud, according or not to a pre-defined pattern. Valid straightedges must fulfil two requirements: have the required length (*e.g.* 2m); and be fully contained within the floor but not closer to its boundary than a defined distance.

   With regard to the positioning of the straightedges around the floor, we investigate three different generation patterns: *Random*, *Grid-Square* and *Grid-Star*.

3. **Associate TLS points to straightedges and calculate deviations and compliance:** For each straightedge generated at Stage 2,

the system identifies the TLS cloud points located under the straightedge, calculates the deviation for the straightedge, and ultimately decides on the compliance of the floor given the specified tolerances.

These three stages are detailed in the sequel.

Note that floors must be controlled by floor *section*, that is a continuous surface delimited by the floor boundary and/or joints. Floors should thus first be divided into conforming test sections. In our implementation, we assume that the 3D model already contains appropriately divided floors.

5.1. Data Pre-Processing

In this section, two important pre-processing steps are described. The first step identifies the set of TLS points from the floor's top face. The second organizes those points in an array data structure that is used to conduct efficient, directed point searches.

5.1.1. Points in the top face of the floor

To identify the TLS points acquired from the floor's top face, we build on the fact that the Scan-vs-BIM system employed in [31] not only associates points to each model object but further associates them to each triangular face defining the surface of the object. As a result, the points on the floor's top face are easily identified as those associated to mesh faces with normal vectors pointing upwards.

5.1.2. Point Search Array Structure

Millions of points may be associated to the floor's top face. In order to accelerate the search for points around the floor, a 2D square array structure is created (see Figure 2). The orientation and extent of the array are determined using the two main directions of the floor (we use the horizontal directions of its bounding box) and a pre-defined array cell size, d_{array} (we use d_{array}=50mm). Each array cell is identified by an index tuple (i, j) – that convert into 2D coordinates on the floor plane – and has an associated list of the TLS points that are on the floor's top face and that fall within the cell's boundary.

5.2. Generation of straightedges

The system generates straightedges by selecting pairs of TLS points on the floor that are spaced by the necessary distance (*e.g.* 2m). The literature review (Section 2.1.1) highlighted that current standards do not prescribe

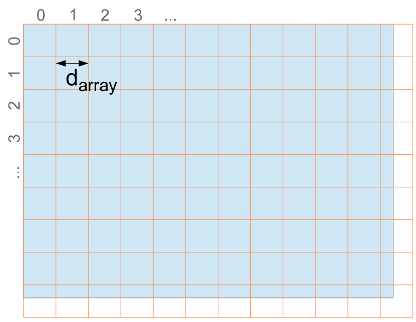


Figure 2: Illustration of the array structure used to accelerate point search on the floor's top face. The blue rectangle is the floor's top face, the array is shown in orange.

the pattern in which straightedges should be positioned on the slab. But, the literature suggests that straightedges may be positioned randomly, or possibly along the lines of a square grid. In this research, these two as well as a third pattern were investigated:

- *Random*: straightedges are randomly generated on the floor.
- *Grid-Square*: a 2D square grid is created with grid lines spaced by 2m and oriented along the main directions of the floor. Straightedges are then generated between the grid line intersections.
- *Grid-Star*, a new pattern that we introduce and that is aimed at providing a more complete analysis of floor flatness by taking advantage of the density of data points available.

The three pattern generation methods are described in Sections 5.2.2 to 5.2.4. Before that, Section 5.2.1 discusses the method we use to validate the length and location of straightedges generated with either of the three methods above.

5.2.1. Validation of straightedges

Each generated straightedge must be validated against two criteria: length, and location.

The distance between the two points must correspond to the specified straightedge length L (*e.g.* $L = 2m$ for global flatness control). However, selected TLS points may not be exactly distant by L. We thus introduce a tolerance factor ϵ on the distance between the two points, *i.e.* we accept straightedges with length $(1 \pm \epsilon)\,L$; we use ϵ=2%.

Then, as illustrated in Figure 3, it must be ensured that each generated straightedge is entirely contained within the floor – *i.e.* it does not cross any of the boundary segments – and is not closer to its boundary than a pre-defined distance $d_{boundary}$.

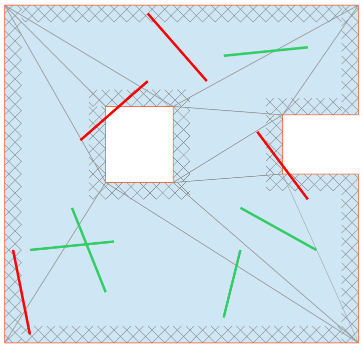


Figure 3: Example of valid (green) and invalid (red) straightedge locations on a floor (blue). The hatched surface highlights the parts of the floor that are closer than $d_{boundary}$ from its boundary.

To check whether the straightedge intersects any of the boundary segments, we work in the 2D coordinate system of the floor's top face, on which we project the straightedge's extremity points, $\mathbf{s}$ ($\rightarrow \mathbf{s}'$) and $\mathbf{f}$ ($\rightarrow \mathbf{f}'$). We then employ the efficient method described in [34].

To additionally check that no part of the straightedge is closer than $d_{boundary}$ to any of the boundary segments, we simply check that $\mathbf{s}'$, $\mathbf{f}'$, and 10cm point increments in between them are not closer than $d_{boundary}$ to the boundary. In our experiments, we use $d_{boundary}$= 40cm.

5.2.2. The Random method

The *Random* method to generate straightedges simply consists in randomly selecting pairs of points from the point cloud associated to the floor's top face. Each straightedge is then validated as described in Section 5.2.1. This process is iterated until a pre-defined number of straightedges has been obtained, *e.g.* 100 straightedges.

The laser scanning measurement process leads to a heterogeneous spread of points on the floor, with most points located near the scanner. Therefore, a fully random selection of pairs of points would lead to a similar heterogeneous spread of straightedges. To ensure that straightedges are homogeneously and widely spread around the floor, we use the homogeneous floor decomposition provided by the array data structure defined in Section 5.1.2 (see also Figure 2). To generate each straightedge, a cell is first randomly selected from the array, and a TLS point randomly selected from those contained in that cell. This point is the first extremity of the straightedge,

s. Then, the second extremity of the straightedge, **f**, is searched among all TLS points associated to the floor's top face. Using the array structure, this search is accelerated by searching for points only within array cells that intersect a circle centred on **s** and with radius L (see Figure 4). Figure 6b illustrates the result obtained; the straightedges are homogeneously covering the floor surface.

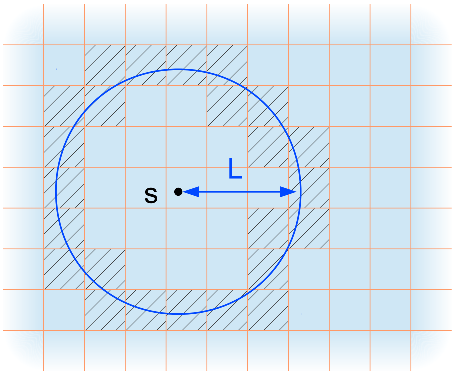


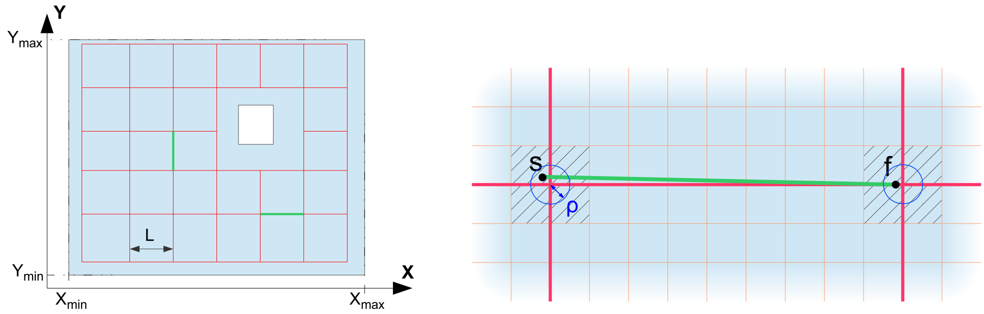
Figure 4: Illustration of the search for **f** using the array structure. **f** is searched among the points located in the hatched array cells.

5.2.3. The Grid-Square method

The *Grid-Square* method aims at creating a 2D square grid with spacing parameter L and then defining straightedges between all pairs of neighboring grid intersections. The orientation and size of the grid is determined using the main directions and dimensions of the floor's top face. Straightedges are generated between neighboring grid intersections as long as these have valid TLS point associated to them (see Figure 5b).

For each grid intersection, a valid associated point is identified as the closest TLS point within a neighborhood defined by the radius ρ (we use ρ= 25mm). To quickly identify which TLS points are within this neighborhood, we use the array structure defined in Section 5.1.2 and test only those points that are within the cells intersecting the circle centered on the grid intersection and with radius ρ (see Figure 5b). If two valid neighbouring grid intersections are found, we then check the validity of the straightedge connecting them, as described in Section 5.2.1.

An example of straightedges extracted using the Grid-Square method is shown in Figure 6c.



(a) The generated square grid. The floor is in blue, the grid in red, and two examples of straightedges are shown in green.

(b) The generation of a straightedge. The array structure appears in orange, the straightedge grid in red, and the straightedge in green.

Figure 5: Generation of straightedges in the Square-Grid method.

Overall, the Grid-Square method does not really make use of the density of points provided by laser scanners and consequently leads to a partial assessment of floor flatness. The random method can more easily make use of the point density by simply increasing the number of straightedges to be generated. However, this process remains random and may require the generation of an unnecessary large number of straightedges. Another straightedge generation method is thus needed that would produce straightedges that altogether cover the floor completely (including in different directions), but that would achieve this without requiring an unnecessarily large number of straightedges to be generated. We propose one that we call *Grid-Star*.

5.2.4. Grid-Star method

This *Grid-Star* method uses a similar grid as the one used by the *Grid-Square* method. But, to ensure that straightedges are generated in all areas of the floor, the process is altered in two ways:

- Additional grid lines and intersections are created at the end of the measurable floor section, even if these are closer than L to their neighbors.

- Instead of generating straightedges using neighbouring grid intersection points only, we generate a number of straightedges around each grid intersection point. For each grid intersection point, we generate many straightedges with their first extremity defined at that point and the second extremities located on a circle (with radius L) around this first extremity. To ensure a homogeneous spread of straightedges around each grid intersection point, the second extremity points are searched at regular angular intervals, α.

Figure 6d illustrates the result obtained for α=10°. The star patterns can be seen around each grid intersection point, and comparison with the previous results (Figure 6b and 6c) shows that a more homogeneous and complete coverage of the floor is achieved with a reasonable number of straightedges.

5.3. Find points under a straightedge and calculate deviation

Once valid straightedges have been generated (using either of the three methods above), the next stage is to identify the points that are located under each straightedge, calculate the deviation for that straightedge and compare it to the tolerance.

Given a straightedge r, we construct a local 3D coordinate system $\mathcal{R} = (\mathbf{x};\mathbf{y};\mathbf{z})$ that uses its first extremity, $\mathbf{s}$, as the origin and its direction, $\mathbf{u}$, as the $\mathbf{x}$ axis. The coordinate system is then entirely defined as follows:

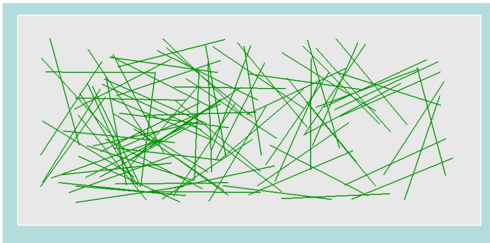
$$\mathbf{x} = \mathbf{u}; \quad \mathbf{y} = \frac{\mathbf{Z} \times \mathbf{x}}{\|\mathbf{Z} \times \mathbf{x}\|}; \quad \mathbf{z} = \mathbf{x} \times \mathbf{y}$$

where $\mathcal{G} = (\mathbf{X};\mathbf{Y};\mathbf{Z})$ is the global coordinate system, and $\times$ is the vector product operator. The homogeneous coordinates of $\mathbf{s}$ and $\mathbf{f}$ in the local coordinate system are thus $\mathbf{s}^r = [0,0,0,1]^\top$ and $\mathbf{f}^r = [L,0,0,1]^\top$. Finally, we define the 3D rigid transformation $\mathbf{M_r} = (\mathbf{R_r}|\mathbf{T_r})$ from the global coordinate system to the local coordinate system of r. Sections 5.3.1 and 5.3.2 below detail the methods for finding the points under the straightedge and calculating the straightedge's deviation.

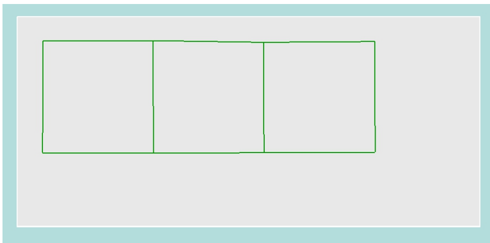
5.3.1. Find points under a straightedge

To find which TLS points are under a straightedge r, we express each point, $\mathbf{p}$, in r's local coordinate system: $\mathbf{p}^r = \left[x_p^r, y_p^r, z_p^r, 1\right]^\top = \mathbf{M_r}\mathbf{p}$. Then, $\mathbf{p}$ is considered to be "under the straightedge" if: $0 \leq x_p^r \leq L$ and $\left|y_p^r\right| \leq \rho$, where ρ is used to define an acceptable neighbourhood around the straightedge for points to be considered "under" it (ρ=25mm). This is illustrated in Figure 7 that also shows how the array structure is used to accelerate the search for points under each straightedge.

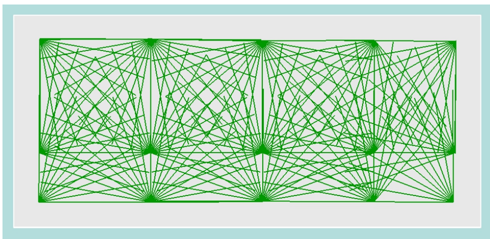
(a) The point cloud of the floor in its original colour.



(b) Random generation of 100 straightedges using the array structure.



(c) Grid-Square method.



(d) Grid-Star with α=10° .

Figure 6: The three different straightedge generation method considered: Random (b); Grid-Square (c); Grid-Star (d).

5.3.2. *Calculate deviation*

The calculation of the deviation of the floor under the straightedge requires the vertical coordinate z of each point $\mathbf{p}$ under it to be well estimated.

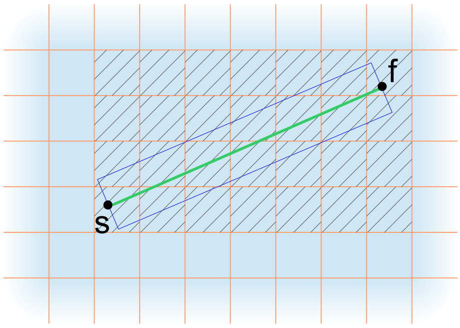


Figure 7: Use of the array structure to efficiently find points under a straightedge. Only points contained in the hatched cells are tested.

To reduce the impact of measurement noise (random error) on the z coordinates, we recalculate these by averaging the values of all points in their neighborhoods; we use ρ=25mm as the neighborhood radius. We denote by $\overline{\mathbf{p}}$ the resulting point.

According to [35], each point's deviation under the straightedge, δ_p^r, should be measured along the global vertical axis and not perpendicularly to the straightedge. We thus calculate δ_p^r using the following formula (see also Figure 8):

$$\delta_p^r = \frac{z_{\overline{p}}^r}{\mathbf{z}^\top \mathbf{Z}} \tag{1}$$

with $z_{\overline{p}}^r$ the z coordinate of $\overline{\mathbf{p}}^r$, *i.e.* $\overline{\mathbf{p}}$ expressed in $\mathcal{R}$.

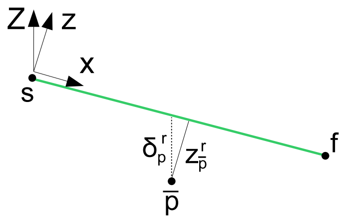


Figure 8: Calculation of the deviation of each point under a straightedge.

The overall straightedge deviation, Δ^r, is then calculated as the difference between the largest and smallest deviations measured for all points $\mathbf{p}$ ($\overline{\mathbf{p}}$) under the straightedge:

$$\Delta^r = max\left(\left\{\delta_p^r\right\}\right) - min\left(\left\{\delta_p^r\right\}\right) \tag{2}$$

The floor is then within compliance, if the measured straightedge deviations, Δ^r, do not exceed the defined tolerances. As discussed in Section 2.1.1, tolerances may be provided for 100% compliance only, or for both 100% and 90% compliance; our system supports both.

6. Automated F-Numbers Method for Flatness Control

We have also digitally encoded the F-Numbers method for floor flatness control, as described in ASTM E 1155-96 [14]. In our implementation, the control procedure is divided in three steps:

1. **Data pre-processing:** The input to this stage is the geometry of the floor (expressed as a triangular mesh) and the point cloud associated to it. The same two data pre-processing steps as for the Straightedge method are then applied, *i.e.*: identification of points on the floor's top face; and construction of the array structure for efficient point search. We thus refer the reader to Section 5.1 for details.

2. **Generate sampling lines:** The input to this stage is the geometry of the top face of the floor and the point cloud associated to that face (organized in the search array structure). The process consists of generating sampling lines and points along those. The sampling must then be validated against several criteria (*e.g.* minimum length of sampling lines).

3. **Measure sample point elevations and calculate F-Numbers:** The elevations of all sample points from the reference horizontal plane are calculated and subsequently used to calculate the F-Numbers F_F and F_L.

The latter two stages are detailed in the following corresponding sub-sections.

Note that, as for the Straightedge method, measurements must be conducted per floor section – *i.e.* continuous floor surface delimited by the floor's boundary and joints. We assume that the 3D model already contains an appropriately divided floor.

Furthermore, the F-Numbers method requires that the floor section be of minimum size, *i.e.* its shortest side is at least 8ft ($\sim$2.4m) long, and its area A is at least 320sq.ft ($\sim$30m^2). These constraints are easily automatically checked using the mesh representation of the floor's top face.

6.1. Generate Sampling Lines

According to [14], sampling lines should be defined in two orthogonal directions, with their overall orientation depending on the dimensions of the slab. If the shortest side of the floor is larger than 25ft, the lines are defined along the longest side of the slab; otherwise the lines are defined oriented 45° . Parallel sampling lines should be spaced by $S_L \geq$4ft (∼1.2m), and sampling points along each line by S_M=12in. (∼ 0.3m).

To generate the sampling lines and points, we first define a 3D coordinate system, $(\mathbf{x}; \mathbf{y}; \mathbf{z})$, local to the floor's top face that uses as origin one of the floor corners connected to the longest side, and is oriented as defined above (see Figure 9). We also define the 3D transformation $\mathbf{M} = (\mathbf{R}|\mathbf{T})$ from the global coordinate system $(\mathbf{X}; \mathbf{Y}; \mathbf{Z})$ to the local coordinate system of the floor's top face.

Sampling locations outside the floor (see Figure 9) are naturally discarded. Furthermore, ASTM E 1155 [14] specifies that locations inside the slab but less than $d_{boundary}$=2ft (∼0.6m) from its boundary must also be discarded, unless the area of exclusion is larger than 25% of the floor section's surface A (see Figure 9).

For each remaining sampling location, the closest TLS point is identified within the neighborhood radius ρ (ρ=25 mm) – this search is accelerated using the point array structure as described earlier. If no TLS point is found, the sampling location is flagged as being invalid.

Once sample points have been defined, each sampling line must itself be validated, which requires that [14]: (a) it is at least 11ft long – we calculate the length as the distance between the first and last valid sampling points on that line; and (b) it contains at least 11 valid sample points. If the line is not valid, it and the corresponding sample points are discarded.

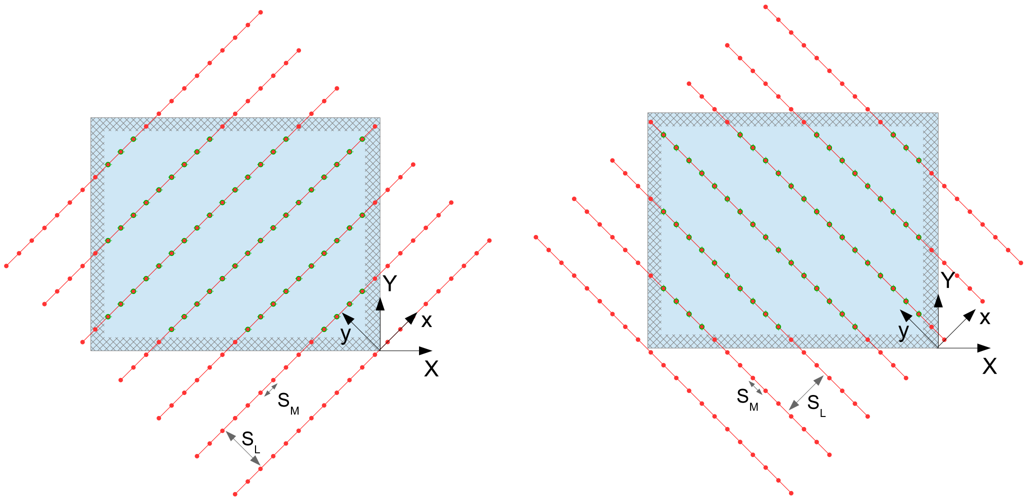
Finally, the calculation of the F-Numbers is only permitted if, for the whole floor section, the number of pairs of valid sample points spaced by 11ft is equal or larger than N_{min} defined as:

$$N_{min} = \begin{cases} 2\sqrt{A} & \text{if } 320ft^2 \leq A \leq 1600ft^2, \\ A/30 & \text{if } A > 1600ft^2 \end{cases} \tag{3}$$

where A is the surface of the floor's top face. If this condition is not fulfilled, the F-numbers cannot be calculated for this floor section.

6.2. Measure sample point elevations and calculate F-Numbers

Similarly as in the Straightedge method, we reduce the impact of measurement noise by recalculating the elevation coordinate, z, of each sampling



(a) Lines generated along the **x** axis. (b) Lines generated along the **y** axis.

Figure 9: Illustration of the generation of sampling lines and locations (dots) used in the F-Numbers method, in the case where lines must be oriented 45° . Valid sample points are shown with a highlighted contour.

point by averaging the corresponding coordinate values of all TLS points in its neighborhood – we use ρ as neighbourhood radius and the array structure to speed up the calculation. The formulas detailed in ASTM E 1155 are finally applied that give the values of the F-Numbers F_F and F_L (see [14] for details).

7. Experiments

The proposed TLS-based system for floor flatness control was tested and validated using two real concrete floors.

In particular, the Grid-Square Straightedge approach was applied to the two floors using both the proposed TLS-based system and the traditional manual control technique. This enabled a direct comparison of their results to validate the proposed TLS-based system. The other approaches – Random Straightedge, Grid-Star Straightedge and F-Numbers – were applied using only the proposed TLS-based system, and their results compared to each other.

7.1. Datasets

Two floors were randomly selected for our experiments. The first is the floor slab (6.40m × 6.70m) of the Acoustic Laboratory of the School of the Built Environment at Heriot-Watt University (see Figure 10a). The second is a section (4.80m $\times$ 8.10m) of the concrete floor slab of the Drainage Laboratory in the same school (see Figure 10b). These slabs are both around 25 years old, thus with potential ageing defects.

(a) Acoustic Laboratory.

(b) Drainage Laboratory.

Figure 10: The two concrete floors used for the experimental testing and validation of the proposed automated Straightedge and F-Numbers methods.

7.2. Manual measurement

For the manual measurement, we have carefully drawn a 2m grid on the floors with a chalk line so that the grid intersections, and consequently the straightedges, match those automatically generated by our system. Measurements were then conducted using a 2m long straightedge and a precision steel rule.

7.3. TLS data collection and Scan-vs-BIM process

The Acoustic Laboratory being a small fully enclosed room, the scanner had to be located on top of the slab, which resulted in a lack of data acquired under it. A second scan was thus acquired from a different location on the slab and the two scans co-registered. In the Drainage Laboratory, the test section of the floor was accessible, and could be scanned from one single location.

All scans were acquired using a FARO Focus 3D [19] and saved in PTX format using the FARO Scene software. The FARO Scene software was also employed to co-register the two scans acquired in the Acoustic Laboratory. Following data acquisition, a 3D BIM model of each room was created using Autodesk Revit, and saved in OBJ format. Then, the approach of Bosché [31] was used to register the laser scans with the 3D models, and match all TLS points to the different objects composing the 3D models of the rooms (see Figure 11). With our two datasets, this process resulted in approximately 6 million TLS points matched to the floor of the Acoustic Laboratory, and approximately 1 million points matched to the floor of the Drainage Laboratory.

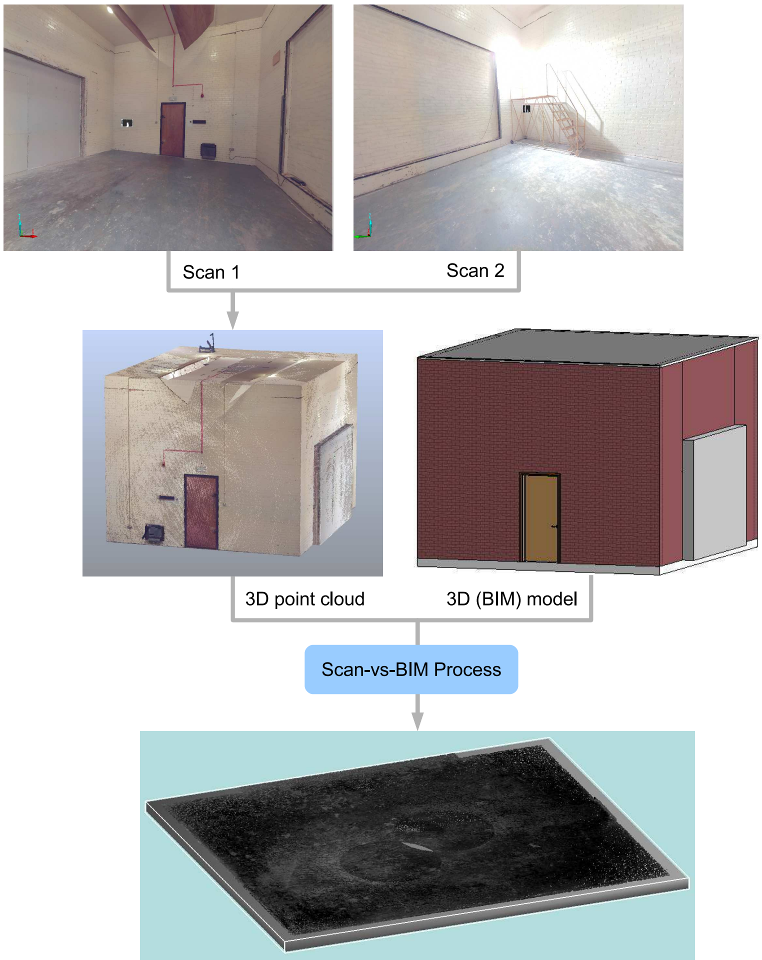


Figure 11: Illustration of the Scan-vs-BIM process with the Acoustic Laboratory data.

7.4. Processing parameters

Our implementations of the Straightedge and F-Numbers methods use a number of parameters. These can be defined by the user through a graphical interface, but the values reported in Table 4 have been found appropriate and were used in all the experiments reported here.

The remaining required parameters simply include the surface flatness tolerances (maximum deviations, or F-Numbers). These are currently provided by the user through a graphical interface. However, as discussed in Section 2.3, it is envisioned that these could be accessed directly from specifications integrated within the project BIM model (*e.g.* by using NBS Create [30]).

Stage	Parameter	Description	Value
Pre-processing			
	d_{array}	Cell size of point search array	50mm
	ρ	Point neighbourhood radius	25mm
Straigthedge processing			
	ϵ	Tolerance on straightedge length	2%
	α	Minimum angle between straightedges (Grid-Star method)	10°
	$d_{boundary}$	Minimum distance of straightedge to floor boundary	40cm

Table 4: Processing parameters.

7.5. Reporting results

Once the software has finished the flatness control calculations, the results can be reviewed in two complementary ways:

- *In the software*: For the straightedge approach, all straightedges are displayed in the 3D environment interface on the floor's top face, and are coloured based on whether they are within tolerance (*e.g.* see example in Figure 13a). For the F-Numbers method, all sampling lines are displayed. In addition to the 3D visualization, the software summarizes all results in a message display window.

- *In a spreadsheet*: The quality control results can also be saved in a spreadsheet that can be explored with common spreadsheet software packages. For the Straightedge method, the spreadsheet lists information for each straightedge (*e.g.* ID, coordinates of extremities, number of points under it, maximum deviation) and on the overall compliance analysis (*e.g.* tolerance, 100% compliance, 90% compliance). For the F-Numbers method, the spreadsheet lists all necessary information as specified in ASTM E1155 [14], namely: for each sampling line, all measured point elevations (and derived d, q and z values) and F_f/F_l values; for the floor section, the F_F/F_L values along with their respective 90% confidence intervals.

8. Results and analysis

8.1. Straightedge approach with Grid-Square method

8.1.1. Quality Performance

Figure 12 summarizes the experimental results obtained for the Grid-Square Straightedge approach (for global flatness control). It gives a top view of the straightedges generated by our system (and subsequently manually measured for comparison), and a summary of the comparison of the results obtained by our system and manually. The following conclusions can be drawn from these results:

- Using 4%, 10% or 25% of the initial point clouds did not have any major impact on the final results – 4% equates to 240,000 points for the Acoustic Laboratory floor and 40,000 for the Drainage Laboratory. This means that it is not necessary to conduct extremely dense scans, which can save quite some time on the overall process, as highlighted in next section.

- Some differences between the deviations obtained using the manual and TLS-based approaches can be observed. Arguably, significant differences can be observed for straightedges 4 and 5; but it is unclear whether this is due to some systematic error in the manual measurement or the laser scanning. These two cases aside, the differences appear small, and this is confirmed by the statistical analysis results reported in the bottom tables of Figure 12. These reveal that the average difference between the manual and TLS-based measurements of the deviation under a straightedge is 1mm or less, and that there is clearly no statistical difference between them.

- Most importantly, not only are the differences between the manual and TLS-based approach small, but the maximum overall deviation (which is used to assess the overall floor compliance) is found by both approaches to be coming for the same straightedge.

Overall, although these results need to be confirmed with additional test data, they suggest that the proposed TLS-based approach outputs straightedge deviations that are similar to those obtained using the traditional manual measurement approach.

8.1.2. Time performance

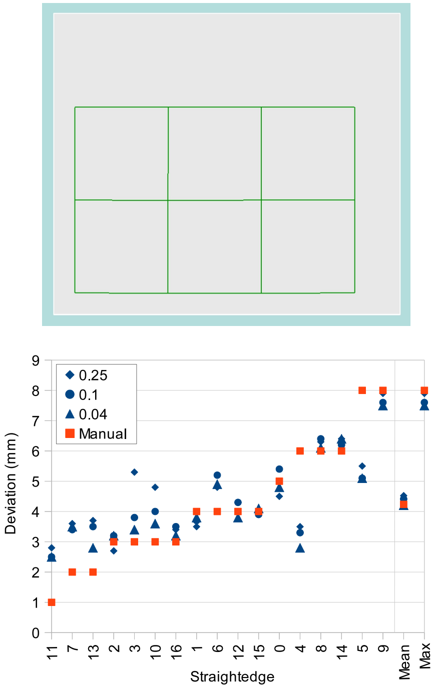
It is also important to compare the time necessary to perform surface flatness control using the manual and our TLS-based approaches. The manual global flatness control required 3 hours (17 straightedges) for the slab of the Acoustic Laboratory and 1.5 hours (10 straightedges) for the Drainage Laboratory slab. In comparison, the TLS-based approach took around 1 hour 50 minutes overall for the Acoustic Laboratory and 1 hour overall for the Drainage Laboratory. Table 5 provides a breakdown of those times. These results highlight two interesting things:

- Half the time required by the TLS-based approach was spent acquiring data (scanning). The rather long scanning times were due to the use of scanning settings enabling the acquisition of data with sufficient accuracy. When compared to standard setting which can give up to 976,000 points per second [19], this lead to an increase in scanning time by a factor of five. Furthermore, the scans were conducted with very high density, that our experiments have shown not to be necessary. It is expected that continuous improvements in scanning technology and the reduction in scan density will lead to significant reductions in scanning times, hence reducing the time required for conducting quality control tasks using the proposed approach.

- The time spent for global flatness control using the Grid-Square method was typically less than 1 minute (in fact around 10 seconds). This indicates that other straightedge generation methods could be employed (*e.g.* Random or Grid-Star) that would deliver more complete and reliable results without impacting the overall flatness control duration.

8.2. Straightedge approach with Random and Grid-Star methods

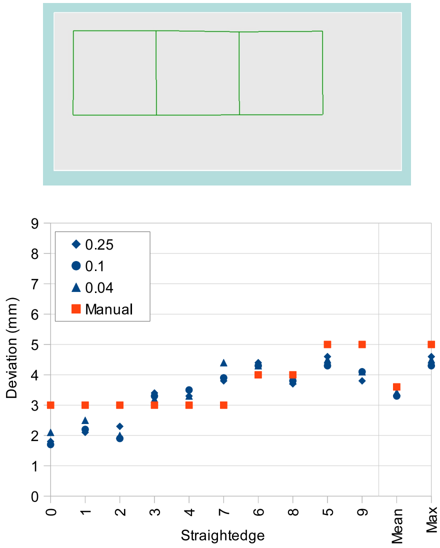
Figure 13 summarizes the results obtained with the Grid-Star and Random Straightedge approaches. Note that to enable a fair comparison of these two approaches, the number of straightedges generated by the Random method was set to the number generated by the Grid-Star method –



Difference (mm)	
Mean	St.Dev.
1.2	1.0

T-Test (two-tail; α=0.05)		
t stat.	t crit.	p-value
0.57	2.12	0.57

(a) Acoustic Laboratory.



Difference (mm)	
Mean	St.Dev.
0.7	0.4

T-Test (two-tail; α=0.05)		
t stat.	t crit.	p-value
1.24	2.26	0.24

(b) Drainage Laboratory.

Figure 12: Quality performance of the proposed TLS-based system. *3D View*: The straightedges generated by our TLS-based system using the Straightedge Grid-Square approach, and subsequently measured manually. *Plot*: Comparison of the individual straightedge deviations obtained by our system (using 4%, 10% and 25% of the initial scan) and by manual measurement; the straightedge are sorted by manual measurement deviation; comparison is also provided for the average and maximum measured deviations. *Table*: Statistical analysis of the difference in straightedge deviations obtained manually and using the proposed TLS-based approach (using 10% of the initial laser scans). The first table provides the mean and standard deviations of the differences. The bottom table summarizes the result of the paired T-Test with null hypothesis "the difference between the deviations is null" and assuming unequal variance.

i.e. 230 straightedges for the Acoustic Laboratory floor, and 320 straightedges for the Drainage laboratory floor. These results highlight a couple of

Process Stages	Acoustic Lab	Drainage Lab
Scanning	2x30 min	30 min
Scan Pre-processing (Faro Scene)	20 min	10 min
Scan-vs-BIM	25 min	15 min
Flatness Control (Grid-Square)	<1 min	<1 min
Total	1 hr 50 min	1 hr

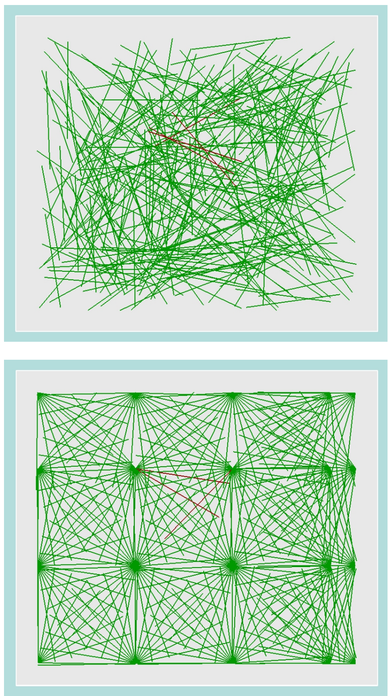
Table 5: Approximate durations recorded when performing the control procedure using the TLS-based approach. Processing times are reported when using 10% of the original scan data. *Scan Pre-processing* refers to the multi-scan registration and point cloud export conducted with the Faro Scene software package; *Scan-vs-BIM* refers to the process described in Section 4; *Flatness Control* refers to the process described in Section 5.

things:

- The two methods provide deviations measurements that widely cover the surface of the floor, but the Grid-Star method leads to more homogeneously spread straightedges.

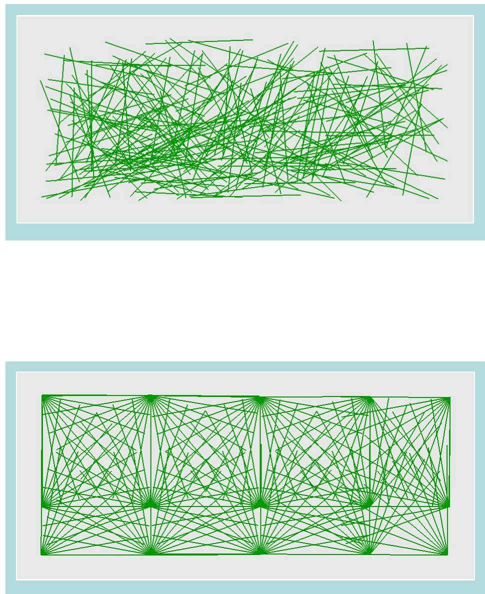
- Both methods achieve similar results with regard to maximum deviation. These deviations are larger than those obtained using the Grid-Square method, but this was expected because these two methods generate straightedges that cover more surface and are thus more likely to identify localized surface irregularities. In fact, all our experiments used a 100% global flatness tolerance of 10mm, and it can be seen that the Random and Grid-star approaches both identified an area of the Acoustic Laboratory floor that was non-compliant, and this area was missed by the Grid-Square method (see Figure 12).

Regarding time performance, the flatness control processing times using the Random and Grid-Star methods were both minimal: less than 15 seconds for the Drainage laboratory, and less than 2 minutes for the Acoustic laboratory (this longer time is due to the larger number of straightedges and larger TLS point cloud associated to the floor). Therefore, the overall durations of the flatness control operation are the same as those reported for the Grid-Square method (Table 5). But in contrast, if the Random and Grid-Star methods were to be applied manually with the same number of straightedges as here, then the overall durations of the control operation would have been in the order of 35 hours for the Acoustic Laboratory slab and 23 hours for the Drainage Laboratory slab. The proposed TLS-based system thus enables more complete and reliable flatness control in significantly shorter times than the manual way.



Stat.	Deviation (mm)		
	Grid-Squ.	Rand.	Grid-Star
Max.	7.6	11.3	11.4
Mean	4.4	4.7	4.5

(a) Acoustic Laboratory.



Stat.	Deviation (mm)		
	Grid-Squ.	Rand.	Grid-Star
Max.	4.3	6.6	6.6
Mean	3.3	3.3	3.5

(b) Drainage Laboratory.

Figure 13: Results achieved with the proposed TLS-based system using the Straightedge Random and Grid-Star approaches. The top images show the top views of the slab with the generated straightedges. The bottom tables report the mean and maximum deviations reported by these two methods in comparison to those obtained using the Grid-Square method.

8.3. F-Numbers approach

Figure 14 summarizes the results obtained by our system using the F-Numbers approach. To be able to assess the appropriateness of the values reported, we also applied the Straightedge Grid-Star approach with 3m (∼10ft) straightedges and compared the results using the rough equivalences summarized in Table 3. The following conclusions can be drawn from these results:

- Similarly to the Straightedge approach, no significant differences are observed when 4%, 10% or 25% of the initial scans are used, which means that it is not necessary to conduct extremely dense scans.

- In the case of the Acoustic Laboratory, the reported F_F value appears consistent with the deviation obtained using the 3m straightedge approach. In the case of the Drainage Laboratory, the values are a little less consistent (F_F=17.9 is normally equivalent to a 9mm gap). This apparent difference may be due to the incomplete surface coverage of the F-Numbers method, and/or simply the approximations in the equivalences between the two methods provided in Table 3.

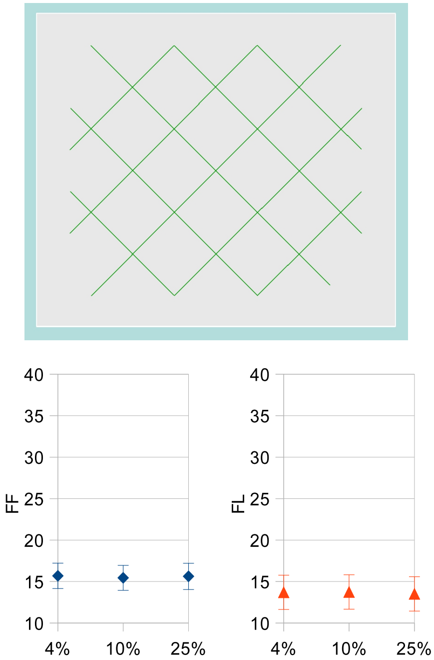
Overall, while these results should be confirmed through more extensive experiments, they suggest that the proposed TLS-based F-Numbers approach provides results that are likely similar to those that would be obtained using traditional measurement methods.

9. Conclusion

TLS and BIM technologies offer great opportunities to improve the completeness, reliability and efficiency of dimensional quality control operations. This paper focused on the case of surface regularity control and presented an approach that integrates TLS and BIM technologies to significantly automate floor flatness control. TLS is used to acquire dense 3D point clouds of surfaces to be controlled. The data is then registered in the coordinate system of the project 3D BIM model, that could be previously augmented with construction specifications, in particular dimensional tolerances. The proposed system then automatically (1) matches TLS points to the BIM model objects, and (2) applies specified dimensional control procedures to the floor data. The Straightedge and F-Numbers flatness control techniques have both been encoded so that they can be applied to any floor section with matched TLS points. Furthermore, for the straightedge technique, three different straightedge generation methods have been considered: Random, Grid-Square and Grid-Star; the latter being a novel method that we proposed.

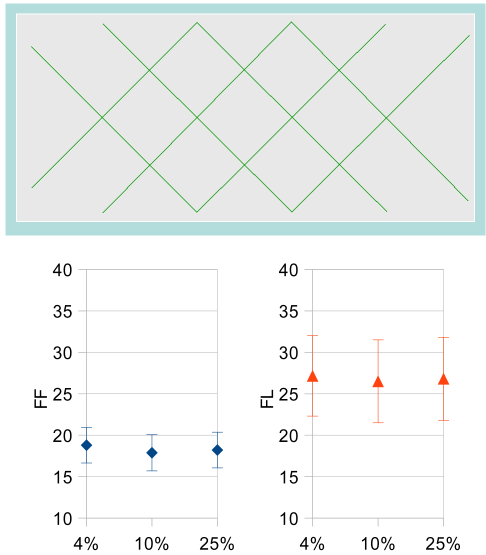
Two real concrete slabs were used as cases studies for experimentally testing and validating the proposed system. The results of these experiments lead to the following conclusions:

- Straightedge approach:



F_F	Straightedge
15.4 (13.9–17.0)	10.8

(a) Acoustic Laboratory.



F_F	Straightedge
17.9 (15.7–20.1)	7.4

(b) Drainage Laboratory.

Figure 14: Results achieved with the proposed TLS-based system using the F-Numbers approach. *Images:* top views of the slabs with the generated measurment sampling lines. *Plots:* F-Numbers with 90% confidence intervals obtained for different TLS point sampling rates. *Tables:* F_F values with 90% confidence intervals (obtained using 10% of the initial TLS datasets) in comparison with the maximum deviations obtained using the Straightedge Grid-Star approach using 3m straightedges.

– In terms of quality performance, the system compares favourably with the traditional manual measurement approach with regard to both individual straightedge deviation and overall floor compliance.
– In terms of time performance, the system is able to conduct a large amount of straightedge deviation measurements in negligible times. This means that more complete, hence more reliable flatness control results can be achieved with potentially significantly shorter durations than if traditional manual methods were used.
– The Random and Grid-Star methods both showed similar per-

formances, generating straightedges covering floor surfaces well. However, the Grid-Star appears better as its surface coverage is slightly better, more homogeneous. Furthermore, the Grid-Star method has the clear advantage of employing a predictable straightedge generation approach, which means that it could be easily re-applied to the data by any stakeholder to confirm the results.

- F-Numbers approach:
  - The procedure described in ASTM E1155 [14] has been implemented. The comparison of its results with those obtained with the 3m straightedge approach suggests that it also performs well, although this requires further validation.
  - The F-Numbers approach could easily be applied using a denser set of sampling lines to get more complete surface regularity analyses. However, we note that ASTM E1155 [14] currently specifies that these lines should not be closer than 4ft – the reason behind this minimum spacing is unclear to the authors.

- Overall:
  - The results demonstrate that TLS can provide data with sufficient accuracy to conduct standard surface regularity control. This is very important, as there has been some (justified) scepticism about whether the accuracy of laser scanners is sufficient for such applications.
  - The results further demonstrate that, for projects designed and planned using BIM models, the proposed approach using TLS and a Scan-vs-BIM -based process could be used to control the regularity of standard surfaces more automatically, reliably (because using far more complete measurements), and faster. In addition to time and cost savings, this would ultimately increase the confidence of contractors and clients as to whether surfaces are within specifications (*i.e.* risk reduction).
  - The control data and results are automatically linked to the project BIM model objects. They can thus be easily shared and controlled by other project stakeholders. Furthermore, since the F-Numbers and Straightedge Grid-Star methods are repeatable, these other stakeholders could easily and efficiently re-apply them to control the reported results.

– Although this paper focused on surface regularity, the proposed system could be employed similarly to perform other types of dimensional control. Furthermore, it could be used not only with TLS, but also with other sensing technologies like photogrammetric systems or ground-penetrating radar – as long as these can acquire 3D data with accuracy sufficient to ensure the reliability of the control results.

Despite being very promising, these initial results still require further validation using datasets from a wide range of surfaces/floors (including newly constructed) and comparable results obtained using traditional manual methods. In fact, a direct comparison of the F-Numbers results obtained by our system with those obtained with current methods remains to be conducted.

The proposed system relies on the availability of a laser scanner and project BIM model. This certainly prevents it from being used on all projects currently. However, it is clear that the AEC/FM industry is adopting these two technologies at an extremely rapid pace, so that they will likely be available on many, if not all projects in the future. The proposed approach will then be widely implementable.

Although the results presented here are promising and the Random and Grid-Square methods can be used in our system to deliver analyses of surfaces that are more complete physically, it is argued that none of the existing surface regularity assessment method (including the Straightedge and F-Numbers methods) provides a unified analysis of the full spectrum of floor waviness frequencies. Therefore, future work could include the investigation of more advanced approaches, such as Fourier frequency analysis techniques, that would overcome this issue. However, it must be noted that the type of results that such more advanced approaches would deliver would then likely require new types of tolerances and standards be defined.

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