Controlling Slab Flatness Automatically using Laser Scanning and BIM

F. Bosché and E. Guenet

School of the Built Environment, Heriot-Watt University, UK
E-mail: f.n.bosche@hw.ac.uk

Abstract -

Developments of Terrestrial Laser Scanning (TLS) and Building Information Modeling (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 slab flatness control. The approach first employs the Scan-vs-BIM principle of [5] to segment TLS point clouds and match each point to the corresponding object in the BIM model. It then automatically applies the Straightedge technique to the TLS points associated with each floor slab, and concludes with regard to their compliance with given tolerances. The approach is tested using data from two real concrete slabs. Results validate the performance of the proposed system when compared with traditional measurements methods. A novel straightedge generation method is also proposed and demonstrated that enables more complete and homogeneous analysis of surface flatness for insignificant additional processing times.

Keywords -

laser scanning; BIM; quality control; surface; slab; flatness; regularity

1 Introduction

Terrestrial Laser Scanning (TLS) is a modern technology that is revolutionizing surveying works. As highlighted in numerous previous research works (*e.g.* [1, 7]), TLS could provide surveyors with the means to conduct far more complete and reliable dimensional controls in manageable times. But, its use in practice remains limited essentially because of some concerns regarding the level of measurement accuracy it provides, and the time required for manual processing of 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 overall control processes. 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 slab flatness control, with the application of the Straightedge method, one of the most common standard flatness control procedures. 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 for negligible additional processing time.

The rest of this paper is organized as follows. Section 2 reviews existing methods for conducting floor regularity control, and particularly the Straightedge method. It 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 5. Results of the experiments conducted to test and validate the proposed system are reported and analysed in Section 6. Conclusions are finally drawn and recommendations for future work made in Section 7.

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"* [10]. The control of surface regularity can be done using different methods, such as: the Straightedge method [10, 2], the F-Numbers method [2, 3], the TR34 method [15] and the Waviness Index method [4]. In the following, we focus on the *Straightedge method* [10, 2] that is traditionally and commonly used.

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 [10]. 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. 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, the multi-part standard BS 8204 [10] provides global tolerances specifically for the surface regularity of direct finished base slabs or leveling screeds. In the USA, tolerances for concrete slab flatness are provided in ACI 117 [3]. 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 tolerance.

Surprisingly, no British standard specifies where the straightedge should be positioned on a given surface. A note in BS 8204 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 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"* [3]. The only more detailed method was found in the CSTB (France) "Avis technique 20/10-193*V1" [11] that suggests (but it is not a standard) 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.

2.2 Terrestrial Laser Scanning (TLS) for Construction Compliance Control

With TLS, a laser scanner sweeps its entire surrounding space with laser light to acquire 3D data points with good accuracy, high density, and great speed. 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.

The potential of TLS for quality control has long been recognized, and [1] proposed a first formalization for integrating project 3D models and sensor systems (in particular TLS) for construction quality control. A first implementation of such a system has then been reported in [7]. The method uses what the authors later called the *Scan-vs-BIM* principle [17], 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 [7], the authors then demonstrate an approach for automatically quantifying positional deviations (*i.e.* deviations equivalent to rigid transformations, such as out-of-plumb deviations of columns). 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, [14] have explored three algorithms for detecting surface flatness deviation. 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 variations of that algorithm are also considered. However, despite a detailed analysis of their performances, the methods presented in [14] do not enable the characterization of defects in ways comparable to current standards. As a result, it is difficult to assess the performance of using TLS in general, and the performance of their approaches in particular, for surface flatness control.

2.3 BIM for Construction Compliance Control

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* [16], 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.

Secondly, design BIM models (with integrated specifications) can support more efficient and robust construction quality/compliance control. In [8], an approach is presented 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 later stages.

3 Contribution and System Overview

We propose an approach that integrates TLS and BIM models and conducts automated floor flatness control. 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 [5, 17] to align the TLS scans in the coordinate system of the BIM model, and match all TLS cloud points to the different 3D objects composing the BIM model. Finally, it automatically applies the Straightedge method 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. Furthermore, the results can be automatically linked to the BIM model, so that they can be easily shared with and reviewed by other stakeholders.

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

Section 4 quickly reviews the Scan-vs-BIM system used at the beginning of the process. Section 5 then describes our implementation of the Straightedge method.

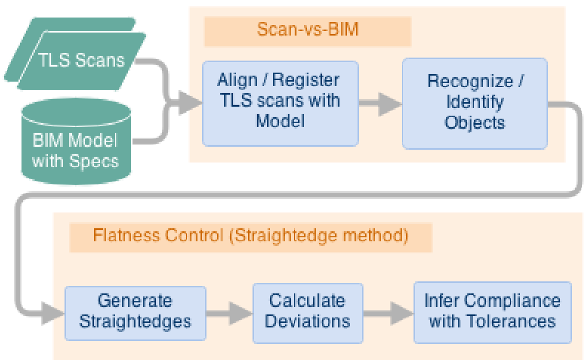


Figure 1: The process followed in the proposed approach and implemented system for floor flatness compliance control given a set of TLS scans acquired on site and the project 3D BIM model.

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 Scan-vs-BIM process [5, 17] consists in aligning the point cloud with the model. For this, we use the approach in [6] based on plane matches, but other approaches can be used. Then, each point of the point cloud is matched to a BIM model object (or none) using a combination of proximity and surface normal similarity metrics. This process segments the initial TLS point cloud into a set of sub-point clouds, one for each of the 3D model objects. 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.

5 Automated Straightedge Method for Flatness Control

We have digitally encoded the Straightedge method for floor flatness control, so that it can be applied automatically to any floor. In our implementation, the control procedure is divided in three steps: 1. Data pre-processing; 2. Generate Straightedges; 3. Associate TLS points to straightedges and calculate deviations and compliance. These three stages are detailed in the sequel.

Note that floors must be controlled by floor *section*, that is defined as 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:

1. Identification of the set of TLS points from the floor's top face. For this, we build on the fact that the Scan-vs-BIM system employed in [5] associates points 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.
2. Organization of the floor's top face points in a 2D square array that will be used to conduct efficient, directed point searches. 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).

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 highlighted that current standards do not prescribe 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 (*Random*; *Grid-Square*) as well as a third pattern (*Grid-Star*) were investigated and 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, 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 $d_{boundary}$. 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, s ($\rightarrow \mathrm{s}'$) and $\mathbf{f}$ ($\rightarrow \mathbf{f}'$). We then employ the method described in [13]. To additionally check that no part of the straightedge is closer than $d_{boundary}$ to any of the boundary segments, we simply check that 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. 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. To generate each straightedge, a cell is first randomly selected from the array, and a TLS point is randomly selected from those contained in that cell as the first extremity of the straightedge, s. Then, the second extremity of the straightedge, $\mathbf{f}$, is searched among all TLS points contained in the cells intersecting a circle centered on s and with radius L. Figure 2b illustrates the result obtained.

5.2.3 The Grid-Square method

The *Grid-Square* method creates a 2D square grid with spacing parameter L and then defines 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. 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). If two valid neighboring 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 2c.

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*.

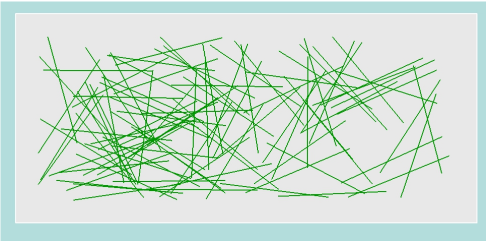
5.2.4 Grid-Star method

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:

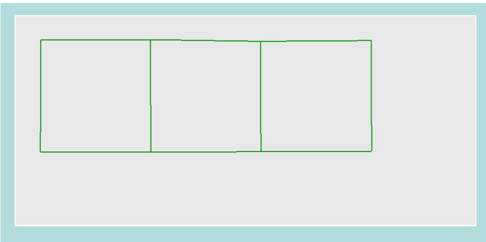
- Additional grid lines and intersections are created at the end of the measurable floor section, even if these are closer than L to their neighbors.
- Instead of generating straightedges using neighboring grid intersection points only, we generate a number of straightedges with their first extremity defined at each grid intersection point and the second extremities located on a circle of 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 2d illustrates the result obtained for α=10°.

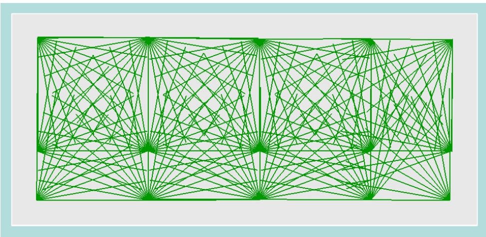
(a) The point cloud of the floor in its original colour.



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



(c) Grid-Square method.



(d) Grid-Star with α=10°.

Figure 2: The three different straightedge generation method considered: Random (b); Grid-Square (c); Grid-Star (d).

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. 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 ($\mathbf{R_r}$ being the rotation matrix and $\mathbf{T_r}$ the translation vector of the transformation).

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 neighborhood around the straightedge for points to be considered "under" it (ρ=25mm).

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. To reduce the impact of measurement noise on the z coordinates, we calculate 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 [9], 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:

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

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

The overall straightedge deviation, Δ^r, is then calculated as:

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

The floor is then within compliance, if none of the measured straightedge deviations, Δ^r, exceeds the defined tolerances.

6 Experiments

The proposed system was tested and validated using two real concrete floors. The first is the floor slab (6.40m $\times$ 6.70m) of the Acoustic Laboratory (AL) of the School of the Built Environment at Heriot-Watt University. The second is a section (4.80m $\times$ 8.10m) of the concrete floor slab of the Drainage Laboratory (DL) in the same school. These slabs are both around 25 years old, thus with potential ageing defects.

The Grid-Square 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 two approaches – Random and Grid-Star – were applied using only the proposed TLS-based system, and their results compared to each other and to the Grid-Square approach.

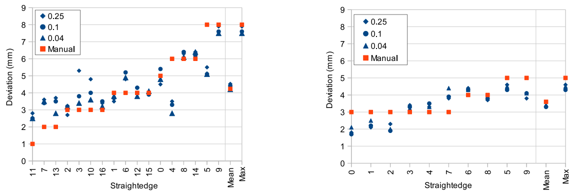
For the manual measurement, we have carefully drawn a 2m grid on the floors with a chalk line so that the grid intersections, and consequently the straightedges, match those automatically generated by our system. Measurements were then conducted using a 2m long straightedge and a precision steel rule.

For the TLS data collection, the AL being a small fully enclosed room, two scans had to be conducted to ensure data was acquired for the entire slab. For the DL slab, one scan was sufficient. All scans were acquired using a FARO Focus 3D [12]. Following data acquisition, a 3D BIM model of each room was created using Autodesk Revit. Then, the approach of [5] 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. This process resulted in $\sim$6 million TLS points matched to the AL floor, and $\sim$1 million points matched to the DL floor.

6.1 Grid-Square results

Figure 3 and Table 1 summarize the experimental results obtained for the Grid-Square approach in comparison with those obtained through manual measurements. To support a detailed comparison, the manual measurements were conducted with straightedges at the same locations as those generated by our system. 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. This means that it is not necessary to conduct extremely dense scans, which can save time on the overall process (see further discussion on time performance below).
- Some differences between the deviations obtained using the manual and TLS-based approaches can be observed. But, these are generally small, and the similarity of results is confirmed by the statistical analysis results that reveal that (1) the average difference between the manual and TLS-based measurements of the deviation under a straightedge is 1mm or less; and (2) there is clearly no statistical difference between them.
- 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 for the same straightedge.



(a) Acoustic Laboratory. (b) Drainage Laboratory.

Figure 3: Quality performance of the proposed TLS-based system. Comparison of the individual straightedge deviations obtained by our system (using 4%, 10% and 25% of the initial scan) and by manual measurement; the straightedges are sorted by manual measurement deviation.

Slab	Difference (mm)		T-Test (two-tail; α=0.05)		
	Mean	St.Dev.	t stat.	t crit.	p-value
AL	1.2	1.0	0.57	2.12	0.57
DL	0.7	0.4	1.24	2.26	0.24

Table 1: Quality performance of the proposed TLS-based system. 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 T-test results are for a paired T-Test with null hypothesis "the difference between the deviations is null" and assuming unequal variance.

It is also important to look at time performance. The manual flatness control required 3 hours (17 straightedges) for the AL slab and 1.5 hours (10 straightedges) for the DL slab. In comparison, the TLS-based approach took around 1 hour 50 minutes overall for the AL slab and 1 hour overall for the DL slab. Table 2 provides a breakdown of those times, highlighting two interesting things:

- Half the time required by the TLS-based approach was spent scanning. The rather long scanning times were mainly due to the need for scanning settings enabling the acquisition of data with sufficient accuracy, which increased the scanning time by a factor of five compared to normal basic settings. Furthermore, the scans were conducted with a high point density, that has been shown not to be necessary. It is expected that smaller point densities along with improvements in scanning technology will lead to significant reductions in scanning times.
- The time spent for 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.

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; global)	<1 min	<1 min
Total	1 hr 50 min	1 hr

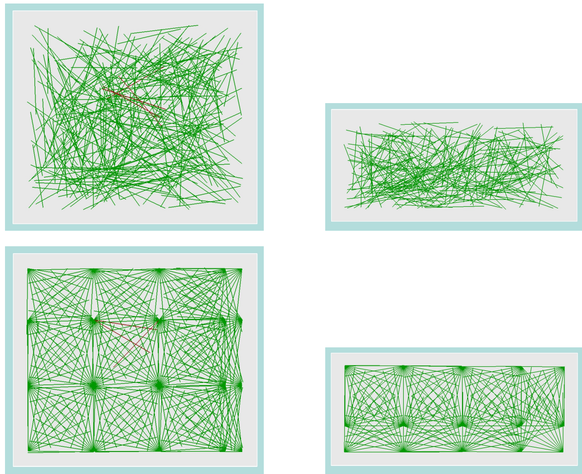
Table 2: Approximate durations recorded with the TLS-based approach (with 10% of the original scan data).

6.2 Random and Grid-Star results

Figure 4 and Table 3 summarize the results obtained with the Grid-Star and Random 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 – *i.e.* 230 straightedges for the AL slab, and 320 straightedges for the DL slab. These results highlight a couple of things:

- The two methods provide deviations measurements that widely cover the surface of the floor, but the Grid-Star method leads to a more homogeneous and complete coverage.
- Both methods achieve similar results with regard to maximum deviation. As expected, these deviations are larger than those obtained using the Grid-Square method 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 3).

Regarding time performance, the processing times using the Random and Grid-Star methods were both minimal: less than 15 seconds for the DL slab, and less than 2 minutes for the AL slab (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 for the Grid-Square method (as detailed in Table 2). 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 AL slab and 23 hours for the DL slab. The proposed TLS-based system thus enables more complete and reliable flatness control in potentially significantly shorter times that traditional measurement methods.



(a) Acoustic Laboratory. (b) Drainage Laboratory.

Figure 4: Results for the Random and Grid-Star approaches. Top views of the slab with the generated straightedges.

Slab	Stat.	G.-Sq.	R.	G.-St.
AL	Max.	7.6	11.3	11.4
	Mean	4.4	4.7	4.5
DL	Max.	4.3	6.6	6.6
	Mean	3.3	3.3	3.5

Table 3: Results for the Random and Grid-Star approaches. Mean and maximum deviations (mm) reported by these two methods along with the Grid-Square method.

7 Conclusion

TLS and BIM technologies offer great opportunities to improve the completeness, reliability and efficiency of dimensional quality control operations. This paper presented an approach that integrates TLS and BIM technologies to significantly automate floor flatness control. The Straightedge control technique has been encoded for application to any floor section with matched TLS points. Three different straightedge generation methods have been considered: Random, Grid-Square and Grid-Star; the latter being a novel method that we proposed. The experimental results lead to the following conclusions:

- 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 results can be obtained in significantly shorter times than if traditional manual measurement methods are used.
- The Random and Grid-Star methods both showed similar performances, 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.

These initial results are very promising but still require further validation using datasets from a wide range of surfaces/floors (including newly constructed) and including comparable results obtained using traditional manual measurements.

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