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Automating surface flatness control using terrestrial laser scanning and building information models

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ABSTRACT

Current practice in the control of surface flatness requires a significant amount of time and labor, and delivers results based on few sample measurements. 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 surface flatness control. The approach employs the Scan-vs-BIM principle of Bosché and Haas (2008) 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 measurement 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.

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 utilization remains labor and time-intensive [2–4], 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 center 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 [2–4,6]. 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 Modeling (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.* [2–4,6]), 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 reliable dimensional control results. However, its use in practice remains limited essentially because of some concerns regarding the 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

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common standard flatness control procedures, the Straightedge and F-Numbers methods. The approach achieves results that compare favorably 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 analyzed 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 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 (2 m in Europe, 3 m in the USA) is used to control *global* flatness, while a smaller ruler (0.2 m in Europe, 0.3 m in the USA) can be used to control *local* flatness.[2] 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 'molded or smoothed surfaces', and 'not molded 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 leveling screeds (see Table 1). It is notable that these tolerances are only for global flatness (*i.e.* deviation under a 2 m 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.

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 2.0 m straightedge (3.0 m in [10]); *Local* flatness with a 0.2 m ruler (0.3 m in [10]).

Source	Surface/floor classification		Tolerance (mm)	
			Global	Local
BS EN 13670 [12]	Not-molded surface		15	6
	Molded 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

In the USA, tolerances for concrete slab flatness are provided in ACI 117 [10]. Similar to BS 8204, ACI 117 provides tolerances for 100% compliance — *i.e.* 100% of the straightedge deviation measurements must be below the given tolerance. However, in contrast with BS 8204, it also requires that a second set of tighter tolerances be defined for 90% compliance — *i.e.* 90% of the straightedge measurements must be within the given tolerance [16] (see Table 1).

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 1 m.

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:

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[2] 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.