Laser Scanning and the Continuous Wavelet Transform for Flatness Control

F. Bosché[a] and B. Biotteau[a]

[a] Centre of Excellence for Sustainable Building Design, Heriot-Watt University, UK
E-mail: f.n.bosche@hw.ac.uk

ABSTRACT

Current methods for surface flatness control in construction are based on sparse measurements and therefore may lead to inaccurate and imprecise results. Previous research has shown that Terrestrial Laser Scanning (TLS), with the accuracy and density of 3D point clouds it can provide, could support more complete and reliable control of surface flatness in construction. However, these previous works have only applied to the TLS data existing methods based on sparse measurements, or used defect detection methods that are not based on the analysis of waviness, that is the frequencies in the floor surface profile. Yet, the underlying surface waviness frequencies generally constitute the key information sought after in surface flatness assessment.

In this paper, we investigate the application of a frequency analysis technique, more particularly the Continuous Wavelet Trans-form (CWT), to TLS point clouds associated to surfaces. The aim is to make full use of the density of points provided by TLS and provide detailed results frequency-wise. We provide the reasoning behind employing the CWT for analyzing frequencies in this context, and report results obtained using data acquired from actual slabs. The CWT results are also compared with those obtained when applying the Waviness Index method. The encouraging preliminary results lead us to suggest a path forward for future development and testing with a view on possibly establishing a new standard test method for floor flatness.

Keywords -

Floor; Flatness; Waviness; Continuous Wavelet Transform

1 Introduction

1.1 Flatness Control Methods

The construction of buildings, infrastructure and other facilities requires geometric accuracy, so that further works can be successfully conducted and the facility will perform as planned. For this reason, numerous types of dimensional tolerances are commonly used, many of which standardized (at national, multi-national and even international level). And as a result, the control of dimensional tolerances is an important activity conducted on jobsites, requiring accurate, rapid and affordable measurement tools and procedures [1].

One important area of dimensional control is the control of the flatness of floors, most typically concrete slabs with or without screeds. For this, varying flatness specifications and control procedures have been developed over time, the most common being the *Straightedge* method, the *F-Numbers* method, and the *Waviness Index* method.

The *Straightedge* method [2] is the oldest one. It requires laying a 3-meter straightedge at varying (random) locations on the floor surface and measuring the largest deviations under it. The floor is within tolerance if none of the deviations exceeds a value specified based on the level of flatness required. This method is simple to understand and apply, and requires basic, inexpensive tools. However, its implementation is time consuming, prone to errors, and generally provides a very partial assessment of the floor flatness (measurements are done at few sparse locations on the floor) in space and in types of deviations.

With the development of modern measurement tools like profilometers, the *F-Numbers* method [3] was proposed. This method requires defining survey lines on the floor and measuring the floor elevations at one-foot intervals along them. A formula is then applied to the measured data that gives two numbers, F_F and F_L, for each line and subsequently for the entire floor. The floor is within tolerance if neither F_F nor F_L is below its corresponding specified values. By its reliance on more modern measurement methods, the F-Numbers method is more time-efficient than the Straightedge method, and also more precise. However, it still is somewhat time-consuming and is hard to understand (the two F-numbers or unit-less and do not seem to relate to anything easily understandable by an operator). It also only provides sparse results both in space (measurements are done along few survey lines sparsely defined on the floor) and in types of assessed deviations. For the latter, it has been shown that the way F_F and F_L are calculated means that the method only reacts to surface undulations with periods 1.5-4ft (F_F) and 15-80ft (F_L) [4].

The flatness of floor surfaces is particularly critical for places like warehouses where forklifts are operated, and Ytterberg [4] has theorized that the operation of forklifts tends to be particularly affected by floor undulations (waviness) with period ranging from 50% to 200% of their wheelbase length, which would typically translate to the range from 2ft to 10ft. The clear limitation of the F-Numbers to cover this range (it only covers the two ends of the range) has led to the development of the *Waviness Index* (WI) method [5]. This method is actually very similar to the F-Numbers method as it is also based on one-foot elevation measurements along manually defined survey lines. However, it then calculates several values of waviness for undulations of period 2, 4, 6, 8 and 10ft – i.e. 60, 120, 180, 240 and 300cm. In addition to providing a coverage of the range of undulation periods discussed above, the outputted WI values are also expressed in centimeter (out-of-flatness deviation) which are easier to understand than the F numbers. However, the method still has three main limitations.

1. Its fairly tedious measurement process limits the amount of survey lines that can be measured, leading to spatially sparse results which may not be representative of the true level of flatness of the floor.
2. The method is still based on measurements along lines although floors a 2D surfaces.
3. The flatness results enable the detection of discrepancies but not directly their localization, which is required for remedying them.

1.2 Laser Scanning for Flatness Control

Terrestrial Laser Scanning (TLS) is a technology that is revolutionizing geometric surveying in construction by its capacity to provide both accurate and dense point measurements very rapidly [1][6][7].

With regard to dimensional control, the current practice tends to apply existing methods to the TLS point clouds (e.g. making point-to-point measurements) so that professionals still do not really exploit the density of measurements. The first approaches to do so, simply visually plotted the deviations of points from a reference surface [8]. While this approach helps in the visual identification of potential defects, it still felt short of automatically detecting and quantifying deviations.

Tang et al. [9] then developed and tested an algorithm (with two variants) to detect flatness deviations in 2D TLS data. However, the detection methods they employ focuses on detecting deviation picks as opposed to characterizing surface waviness. Yet, as seen earlier, waviness assessment is a critical aspect of surface flatness characterization.

Following a different approach, Bosché and Guenet [10] have encoded the Straightedge and F-Numbers approach for automated application on TLS point clouds of floors. The advantage of the automated system is that the density of measurement (i.e. number of straightedge measurements, or number of survey lines assessed in the F-Numbers method) can be increased without significant impact on the time necessary to apply the method (minutes at most). While this addresses the first limitation identified earlier, the two other ones remain.

1.3 Contribution

In this paper, we present a novel approach to floor flatness control using TLS, as well as preliminary results. The approach is based on the application of the Continuous Wavelet Transform (CWT) to the floor elevation profile. We show that this method has the potential to address the limitations of current standard methods.

Section 2 presents the CWT method. Preliminary results are then reported in Section 3 and concluded with an overall Discussion in Section 4.

2 Continuous Wavelet Transform (CWT)

The *Wavelet Transform* is a signal analysis method that emerged as a method overcoming the limitations of the Fourier Transform (FT) and Short-Time Fourier Transform (STFT) methods. The FT enables the accurate detection of frequency components in a signal, but is not able to report where along the signal the detected frequencies are located. The STFT partially addresses this limitation by windowing the input signal through its convolution with a fixed-width square signal. However, the method is ineffective to both accurately detect and precisely locate frequencies spread over a wide range. In contrast, the *Wavelet Transform (WT)* aims to convolve the input signal with a *wavelet* function at different locations along it and at multiple scales. Wavelets take their name from the fact that their energy is contained within a short period, and they typically have one *center frequency* f_c. Therefore, the convolution of a wavelet at multiple scales and locations along an input signal leads to the detection of specific frequencies and specific locations.

Several variants of the WT exist and have been developed for very different applications. For example, the Discrete Wavelet Transform is showing important application in signal compression. In contrast, the *Continuous Wavelet Transform (CWT)* is more appropriate to pattern detection in a signal (the pattern being that of the wavelet). The CWT thus appears theoretically well suited to the problem of surface waviness characterization.

Applying the CWT, like any other WT, requires the selection of the *mother wavelet*. One common CWT wavelet is a *Mexican Hat* wavelet. As show in Figure 1, the wavelet is composed of one main, centered frequency undulation, and thus seems appropriate to the detection of flatness defects. The *center frequency* of the Mexican Hat wavelet is 0.252. By convolving an input signal with the Mexican Hat at a given scale a, undulations of *characteristic frequency* f can be detected; f can be simply calculated as:

$$f = \frac{f_c}{\delta_p a} \qquad (1)$$

where δ_p is the point sampling period in the input signal [11].

More details about the Wavelet Transform, its variants and fields of applications can be found in [11].

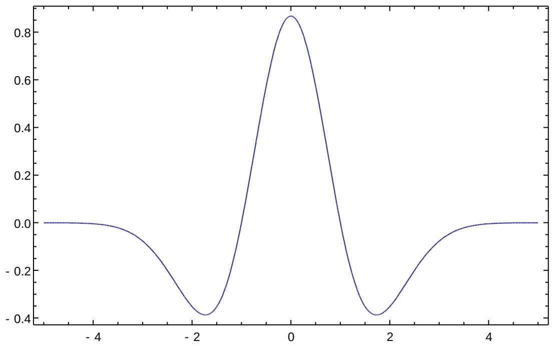


Figure 1. The Mexican Hat wavelet.

3 Preliminary Results

3.1 Dataset

We have conducted preliminary experiments using two existing concrete slabs of university laboratories. The slabs are the same as those used in [10]. The first Acoustic Lab (AC) slab is 6.4m x 6.7m. The second Drainage Lab (DL) slab is 4.8m x 8.1m. The two slabs have been laser scanned. Note that the Acoustic Lab slab required two scans that were subsequently merged. Figure 2(a) shows the DL slab.

(a)

(b)

Figure 2. The DL slab (a) and the point cloud associated to its top surface (b)

3.2 Preprocessing

Using the approach described in [10], the subset of cloud points corresponding to the top surface of the slabs is segmented out of the entire point cloud (Figure 2(b)). Because this point set can still contain millions of points, it is subsequently organized in a 2D square array structure that enables fast nearest-neighbor searches. Finally, to reduce the impact of laser scanning measurement noise on the calculation of point elevations, a mean filter is applied to the points' elevations (*i.e.* coordinates) using a neighborhood radius ρ = 25 mm.

3.3 1D CWT Implementation

We have implemented a 1D CWT algorithm that applies a Mexican Hat -based CWT to elevation profile survey lines defined using the same approach as [10], that is: survey lines are defined at regular intervals δ_l. In the results reported here, we use δ_l= 30cm, which leads to 34 survey lines for the DL floor, and 38 survey lines for the AC floor. A survey line cannot extend closer to the floor boundary than $d_{boundary}$ (we use $d_{boundary}$ = 30cm). Then, survey points are sampled along each line at regular interval δ_p, leading to the establishment of the survey line elevation profile. In order to achieve a good resolution in the localization of undulation frequencies along survey lines, we use δ_p = 1cm.

The CWT is then applied to each survey line elevation profile. For this, we have used the free library *cwtlib* [12]. Note that the maximum scale a_{max} at which the CWT may be applied can be identified using Equation (1) in a reverse manner. Considering a maximum undulation period of 10 ft ≈ 300 cm (see Section 1.1), that is a maximum characteristic frequency f = 0.0033 cm^{-1} (1/300), we get a_{max} = 75.

3.4 1D CWT Results

Figure 4 illustrates results obtained for six survey line elevation profiles randomly selected from the DL and AC cases. The CWT transform plots shown in lines 2 and 4 of the figure are commonly called *scalograms*. With the colormap employed here, a red color indicates positive correlation between the signal and the wavelet, *i.e.* convex undulation is detected at the given location and scale. A blue color indicates a negative correlation, *i.e.* a concave undulation is detected. The shaded parts of the scalograms are discarded because they correspond to locations at which the wavelet falls partially outside the profile data, and therefore the results are not meaningful.

The results show several things. First of all, as expected, the Mexican Hat -based CWT reacts well to waviness in the elevation profiles present at varying scales. Furthermore, it shows the distinct advantage over dissociating concave elevations profiles from convex ones. Finally, the scale at which the CWT reacts appears to correspond to the period of the corresponding undulations. For example, the elevation profile of Figure 4(e) – enlarged in Figure 3 – shows a singular convex undulation of period ~150cm centered at ~180cm along the survey line. The CWT response then shows a convex pick at that the scale ~35 that does correspond to a characteristic period of ~150cm. Similarly, the elevation profile in Figure 4(c) shows a singular concave undulation of period ~120cm centered at ~320cm along the line. At that location, the CWT response does detect a clear concave pick at the scale ~25 that corresponds to a characteristic period of ~100cm.

While these results are clearly very promising, it is unclear at this stage what level of response from the CWT constitutes a defect. While this question will not be fully answered in this manuscript, we have conducted some further analysis aiming to provide some preliminary answer to this question, by comparing the CWT results with those obtained with the Waviness Index method, applied to the same survey lines.

3.5 Comparison with Waviness Index

We have also developed an algorithm that automatically applies the Waviness Index method to the point set of a floor surface. The method follows the procedure described in Section 3.3 and in [10] to define survey lines. It then automatically applies the procedure defined in the standard ASTM R 1486 [5]. First of all, note that we use the exact same survey lines as for the CWT method, so that results can be compared per line. Second, the advantage of the Waviness Index method over other existing standard methods is that it provides sub-results (called LAD) for undulations of period 60, 120, 180, 240 and 300cm (these periods are obtained by having an underlying variable *k* taking the values 1, 2, 3, 4 and 5), so that the comparison with the CWT method can not only be done overall, but also for each undulation period.

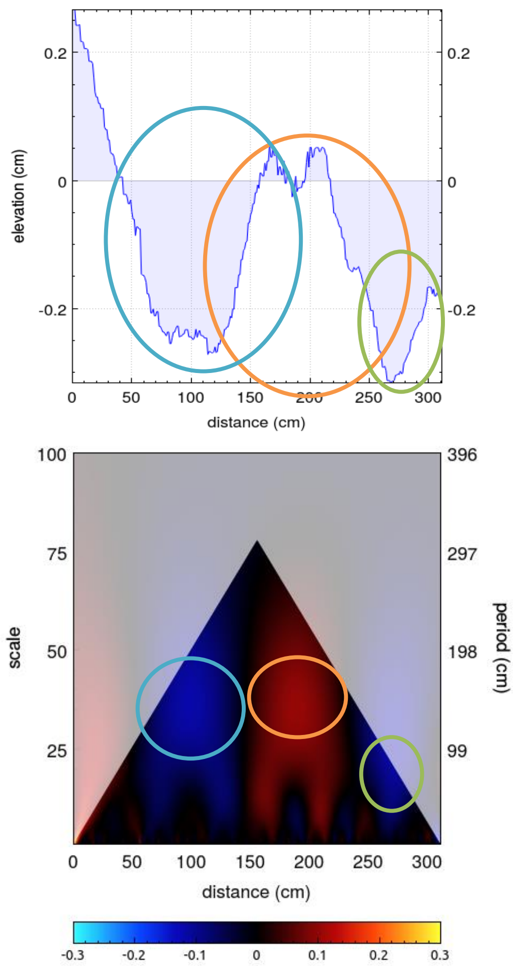


Figure 3. Enlargement of Figure 4(e). The detected are highlighted in the CWT plot and the elevation profile.

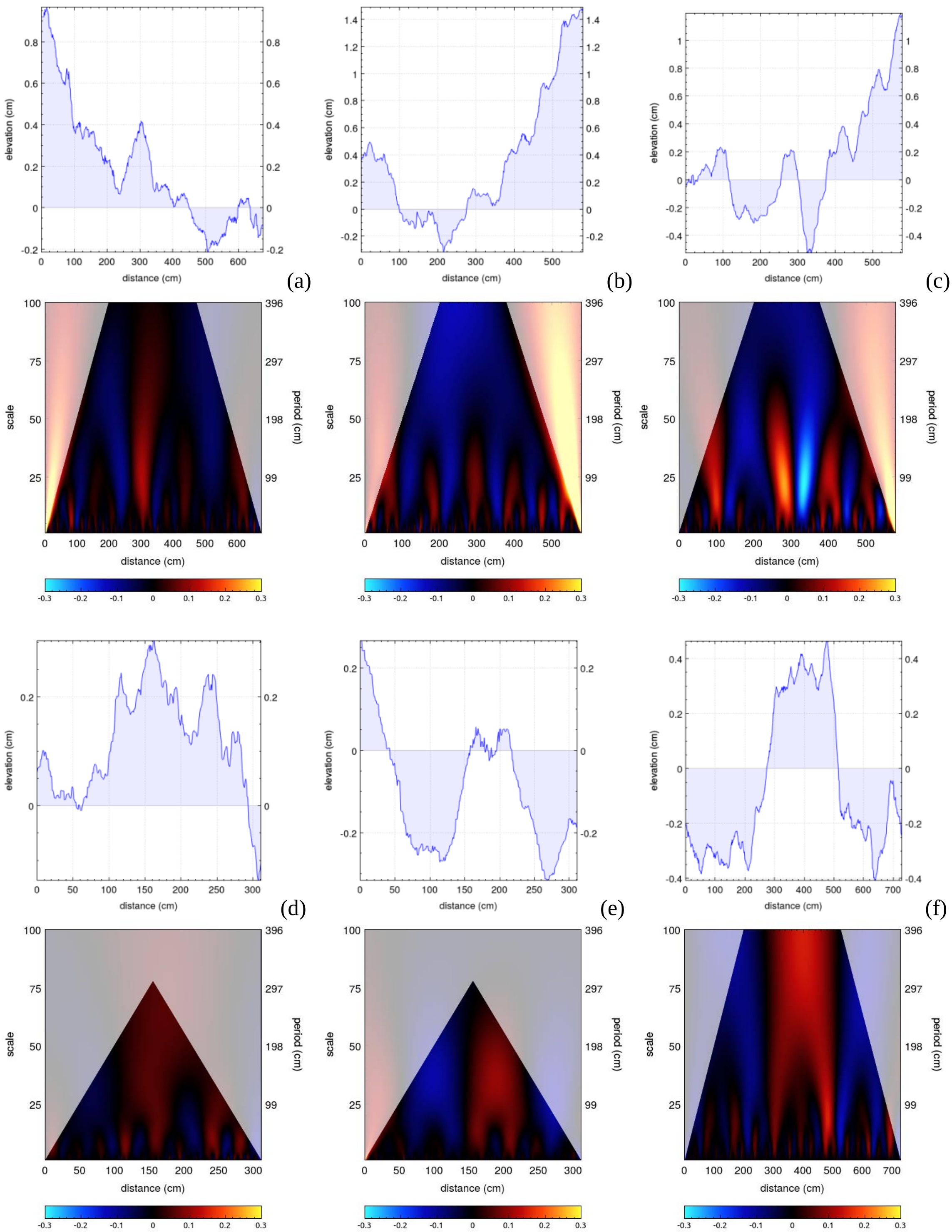


Figure 4. Results obtained when applying the Mexican Hat -based CWT to six elevation profile lines of the DL and AC labs. Rows 1 and 3 show the elevation profiles along the survey lines. Rows 2 and 4 show the CWT transform plots (scalograms) for the elevation profile just above

To perform the comparison between the two approaches we calculate CWT responses corresponding to the LAD values using a similar root mean square RMS formula [5] , that is:

$$\mathrm{CWT}_{L,a} = \sqrt{\frac{\sum_{i=1}^{imax_{L,a}} CWT_{L,a,i}^2}{imax_{L,a}}} \quad (2)$$

where $CWT_{L,a,i}$ is the CWT response at the scale a, at the i^{th} sampled location along the line L; $imax_{L,a}$ is the number of incremental locations where $CWT_{L,a,i}$ can be calculated along the line.

We also calculate, for each line L, the overall CWT response (i.e. integrating the results at multiple scales) using the same weighted root mean square formula as the WI method [5], that is:

$$\mathrm{CWT}_L = \sqrt{\frac{\sum_{a=1}^{amax} imax_{L,a}\mathrm{CWT}_{L,a}^2}{\sum_{a=1}^{amax} imax_{L,a}}} \quad (3)$$

where $amax$ is the number of scales considered. In the context of the comparison conducted here, this is the set of five scales that correspond to the same undulation periods as those considered by the WI method (i.e. 60, 120, 180, 240 and 300cm; or k = 1 to 5). The scales are calculated by using Equation (1) in a reverse way.

Figure 5 shows a scatter plot of the 295 pairs of values ($\mathrm{LAD}_{L,k}$, $\mathrm{CWT}_{L,a}$) obtained for each of the 76 survey lines (L) and the 5 k (and corresponding a) values. Figure 6 shows a scatter plot of the pairs of value (WI_L,CWT_L) obtained for all 76 lines. The results in Figure 5 show a certain correlation between the WI and CWT results. In fact, the correlation R^2 value is only 0.67. Yet, a level of disparity between the WI_L and CWT_L values remains present. The results in Figure 6 indicate an even stronger correlation when combining all five undulation periods. The correlation R^2 value is in fact 0.84.

While these results altogether show a strong positive correlation between the WI and CWT values, thereby confirming the value of the proposed approach, this correlation is not as strong at the period level. A more in-depth analysis of the results offers a likely explanation for this. Indeed, it is observed that the correlation is particularly poor for shorter undulation periods, especially 60cm (k = 1), for which the R^2 value is 0.60. Looking at the measurement profiles considered by both approaches, it is observed that the measurement sampling of the WI method, i.e. every 30cm can easily lead to failed detections of undulations of period 60cm. Figure 7 shows an example of elevation profile for one line as measured using our method (i.e. with measurements every 1cm) and as measured using the WI method. The undulation of period 60cm centered at the location 130cm along the line is essentially missed by the WI measurement method, while it is not by the CWT-based method (this is also the case for the following concave defect with shorter undulation period). This leads to the conclusion that the lower correlation observed in Figure 5 seems due to the sparse measurement required by the WI method leading to imprecise estimations of the $\mathrm{LAD}_{L,k}$, particularly at low periods.

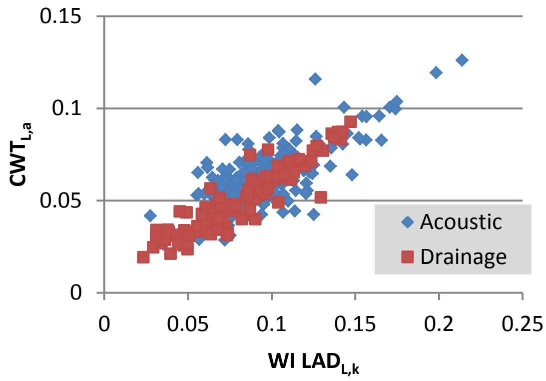


Figure 5. $\mathrm{CWT}_{L,a}$ vs. $\mathrm{LAD}_{L,k}$ for each survey line and for undulation periods 60, 120, 180, 240 and 300cm

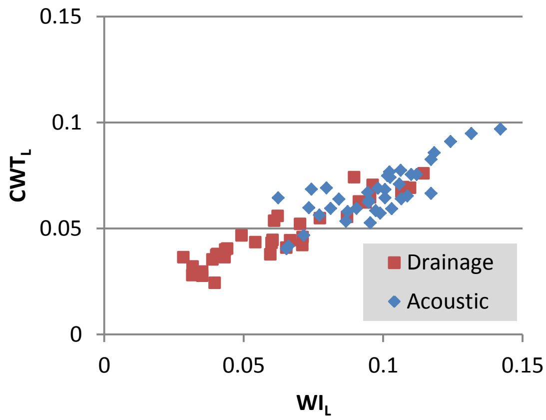
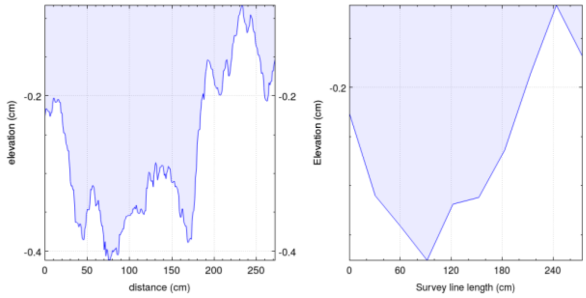


Figure 6. CWT_L vs. WI_L for each survey line

4 Conclusion

This paper presented a novel approach to floor flatness control that harnesses the measurement density that TLS can deliver and the power of the CWT to accurately detect and locate undulations of any frequency in a floor elevation profile.



(a) (b)

Figure 7. The elevation profile for Line 4 as measured with our method (a) and the WI method (b)

Results obtained using the Mexican hat mother wavelet and data acquired from two existing concrete slabs have shown very promising results. The proposed method has unique advantages over existing methods, including the most recent Waviness Index method:

1. Floor surfaces can be analyzed densely and efficiently;
2. The analysis provides a very high resolution in undulation periods – the results in Figure 4 includes results for 100 frequencies, while the WI method only considers five;
3. The outputted scalograms enable an effective visualization of the results, and detection of potential defects.
4. It is theoretically possible to assess floor flatness directly in 2D – although this has not been demonstrated in this paper.

A comparison of the results obtained with the proposed method against those obtained with the WI method shows that the proposed method provides at least as good results as the WI method, and is in fact likely superior to it.

Nonetheless, further experiments clearly need to be conducted to confirm this potential. These should particularly consider many more, also larger, concrete floors. Further, work should establish the correlation between CWT response levels with actual defects (i.e. thresholds) based on varying specified levels of flatness. In that regard, other mother wavelets could also be investigated. Finally, the possibility to directly analyze the 2D elevation profile of floors (as opposed to using survey lines) remains to be demonstrated – although this possibility is theoretically supported by the literature.

References

[1] Akinci B., Boukamp F., Gordon C., Huber D., Lyons C. and Park K. A formalism for utilization of sensor systems and integrated project models for active construction quality control, *Automation in Construction*, 15:124-138, 2006.

[2] British Standards Institution (BSI), *BS 8204 - Screeds, bases and in situ flooring*, 2009.

[3] ASTM International, *ASTM E 1155-96 - Standard test method for determining F_F floor flatness and F_L floor levelness numbers*, 2008.

[4] Ytterberg C.N. *Flatness Tolerances For Random-Traffic Floors*, Technical Report, The Aberdeen Group, 1996.

[5] ASTM International, *ASTM E 1486 - Standard test method for determining floor tolerance using Waviness, wheel path, and levelness criteria*, 2010.

[6] Cheok G.S., Stone W.C., Lipman R.R. and Witzgall C. LADARs for construction assessment and update, *Automation in Construction*, 9:463-477, 2000.

[7] Bosché F., Haas C.T. and Akinci A. Automated recognition of 3D CAD objects in site laser scans for project 3D status visualization and performance control, *ASCE Journal of Computing in Civil Engineering*, 23:311-318, 2009.

[8] Schafer T. and Weber T. Deformation measurement using terrestrial laser scanning at the hydropower station of Gabcikovo, In: *INGEO 2004 and FIG Regional Central and Eastern European Conference on Engineering Surveying, FIG*, Copenhagen, Denmark, 2004.

[9] Tang P., Akinci B. and Huber D. Characterization of laser scanners and algorithms 505 for detecting flatness defects on concrete surfaces, *ASCE Journal of Computing in Civil Engineering*, 25:31-42, 2011.

[10] Bosché F. and Guenet E. Automating surface flatness control using terrestrial laser scanning and building information models, *Automation in Construction*, 44:212-226, 2014.

[11] Addison P.S. *The Illustrated Wavelet Transform Handbook: Introductory Theory and Applications in Science, Engineering, Medicine and Finance*, 1st edition, CRC Press, 2002.

[12] Karpenko S. *Cwtlib, continuous wavelet transform library*, http://sourceforge.net/projects/cwtlib/, Accessed: 05/12/2014.