Automatic Surface Flatness Control using Terrestrial Laser Scanning Data and the 2D Continuous Wavelet Transform

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Abstract –

Evaluating flatness defects in surfaces during the construction of a building can prevent problems during subsequent construction tasks or the operation phase. An area of particular interest is that of the flatness of warehouse slabs on which pallet-transporting equipment is operated (nowadays including robots). Flatness control has typically been done with extensively manual methods, such as the Straightedge, F-Numbers or Waviness Index methods. However, these are time-consuming, based on very sparse measurements, and conduct assessment in linear ways only (i.e. in 1D along survey lines, as opposed in 2D on the entire surface), which can lead to inaccurate assessment. This paper presents a novel approach that takes advantage of (1) Terrestrial Laser Scanners (TLS) to speed up data acquisition and provide precise and dense 3D measurements of surfaces; and (2) the 2D Continuous Wavelet Transform (CWT) to deliver a 2D wavelength analysis of surface data with high resolution both spatially and in the frequency domain. The value of the proposed method over existing approaches is discussed and demonstrated with a first experiment conducted with a real concrete slab.

Keywords –

Surface; Flatness; Control; Wavelet Transform; 2D

1 Introduction

Construction is about the building and installation of components in the three-dimensional (3D) world. An important aspect of the control of construction quality is the verification that all components have indeed been built or installed in their specified location and shape [1] [2]. This may be collectively referred to as *dimensional quality control*.

Dimensional quality control is interested in many kinds of geometric measures, and the one focused on here is *surface flatness*. Surface flatness is an important part of dimensional quality control because the built environment remains largely made up of components with planar surfaces. This is due to the relative ease of constructing such surfaces, but in the case of floors this is even a matter of functionality requirement.

Ensuring that planar floors are indeed flat is important in houses for comfort and for preventing warping of floor finishing or furniture. Local planarity is also an important requirement of road surface to ensure comfortable driving [3]. And the requirements for flatness can be even greater in contexts such as television studies (where the travelling motion of cameras must be as smooth as possible) or warehouses where forklifts (now increasingly robotic ones) must travel fast and safely, without the risk of losing their loads due to vertical vibrations resulting from uneven floors [4].

1.1 Traditional Flatness Control Methods

Various flatness specifications and control procedures have been developed over time, with new methods typically being proposed as a result of the availability of improved measurement technologies.

The *Straightedge* method [5] is the oldest flatness measurement method. It is based on the measurement of deviations under a 3-meter straightedge that is manually and randomly laid on the floor. The floor is within tolerance if none of the deviations exceeds a value specified. 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 partial assessment of flatness in both the spatial domain (due to the sparsity of measurements typically conducted) and frequency domain (only one surface wavelength, 3m, is considered).

The *F-Numbers* method [6] and later the *Waviness Index* method [7] emerged from the development of measurement tools like profilometers. Both methods require the delineation of survey lines on the floor and the measurement of the floor elevation at one-foot intervals along them. Formulas are then applied to the measured data to that calculate a few metrics summarizing the level of flatness. For the F-Numbers methods, these metrics include the F_F (floor flatness) and F_L (floor levelness) numbers, for each line and subsequently for the entire floor. For the Waviness Index method, five Waviness Indices (WIs) are calculated for each line and for the floor.

By their reliance on more modern measurement methods, the F-Numbers and Waviness Index methods are more efficient and precise than the Straightedge method. While the F-Numbers provides waviness information for two different wavelengths (approx. 60cm and approx. 500cm), the Waviness Index method extends those to five (60, 120, 180, 240 and 300cm). The Waviness Index method is thus the one that currently covers the frequency domain the best, albeit for only 5 spatial wavelengths. It should be noted though that these wavelengths were selected specifically to cover the range of wavelengths from 60cm to 300cm that are most likely to impact the operation of forklifts typically used in warehouses (the range is selected to correspond to 50% to 200% of their wheelbase length) [3]. The Waviness Index method was therefore designed to control a range of distances not covered by the F-Numbers method.

Nonetheless, despite its superiority, the Waviness Index method still presents four main limitations:

1. *Partial spatial analysis*: Its measurement process remains fairly tedious with the user having to mark survey lines on the floor, then carefully roll the profilometer along the lines and finally compute the WIs from all measurements. As a result, the number of measured survey lines is typically small, leading to spatially sparse results which may not be representative of the true level of flatness of the floor.
2. *Partial frequency analysis*: The method is limited to the study of five specific wavelengths within the [60cm;300cm] range – in fact experimental results previously reported by the authors even suggest a weakness of the method for the study of the wavelength 60cm [8]. It would be of interest to develop a method that considers more wavelengths within that range but also outside that range.
3. *No direct localisation of defects*: The WIs enable the detection of discrepancies but not directly their localization, although this information is important for remedying the defects. Further manual analysis of the results is required to localise the problematic areas.
4. *1D instead of 2D analysis*: The method is still based on measurements along lines. Floors are inherently 2D surfaces and so flatness should be assessed in 2D.

1.2 Terrestrial Laser Scanning and State-of-the-art Research on Flatness Control Methods

Terrestrial Laser Scanning (TLS) is revolutionizing geometric surveying in construction by its capacity to provide both accurate and dense point measurements very rapidly [9] [10] [11].

Early works on the application of TLS to dimensional control aimed at color-mapping the deviations of the measured points from a reference surface, which enabled a visual detection of areas of potential concern [12]. However, these first works did not aim to automatically detect these areas or quantify the deviations. Tang et al. [1] may be the first to have tried to address this for planar surfaces. They propose an algorithm (with two variants) to detect flatness deviation peaks in 2D TLS data (from a planar reference surface). However, this approach is limited by the fact that it focuses on detecting the maximum(s) of the signal amplitude (i.e. deviation from the reference surface), while existing standards on flatness control clearly highlight the need to characterize surface waviness, not just amplitude.

Bosché and Guenet [2] show how the Straightedge, F-Numbers and Waviness Index methods can be encoded for automated application to TLS point clouds of floors. The main advantage of that approach is that it is fully automated and thus very efficient. As a result, they show how the density of measurements (i.e. number of straightedge measurements, or number of survey lines assessed in the F-Numbers and Waviness Index methods) can be increased significantly at no cost (time-wise), thereby addressing the limitation (1) above (‘*partial spatial analysis*’). Nonetheless, the other three limitations still apply.

In [8], Bosché and Biotteau propose a novel approach to flatness control based on the automated analysis of wavelength along survey lines virtually surveyed in the dense TLS point clouds of floors (similarly as in [2]) using the Continuous Wavelet Transform (CWT). This approach is shown to be powerful as it addresses both limitations (2) and (3) above. By measuring points at shorter increments along the survey lines (1cm instead of 30cm used by the F-Numbers and Waviness Index methods; this is made possible by the density of measurement provided by TLS), the authors show that the wavelengths present in a survey line elevation profile can be automatically detected with great precision in both the frequency and spatial (i.e. along the line) domains.

Figure 1 shows an example of result obtained for a survey line. The authors validate the approach by demonstrating a correlation of the results obtained by their approach with those obtained with the Waviness Index method. In fact, the results even suggest a potential weakness of the Waviness Index method for the 60cm wavelength. Nonetheless, the CWT method in [8] still presents two limitations:

1. The method analyses flatness along survey lines (1D) as opposed to over the entire surface (2D), which makes the overall analysis of a surface somewhat complex. Surface waviness is inherently a 2D matter and so should be studied in 2D; and
2. While Bosché and Biotteau show visually how their method is able to detect and localize any wavelength along survey lines, they did not actually present a method for the automated localization.

A method is still needed that achieves all this.

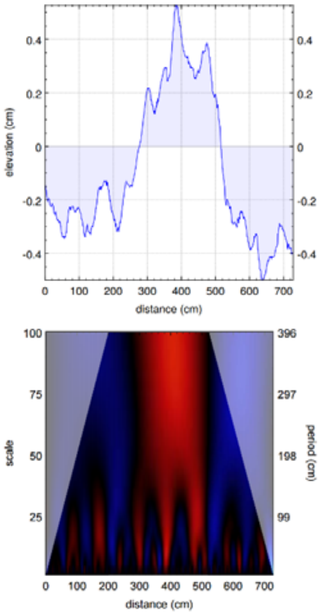

Figure 1. Example of result obtained for the analysis of the elevation profile along a survey line using the 1D CWT method presented in [8].

1.3 Contribution

This paper presents a method that extends that of [8] to 2D and that automatically feeds back to the user the areas of concern regarding the overall flatness. This method is thus the first that addresses all the limitations found in the current state of the art.

Section 2 presents the 2D CWT-based detection and localization method. Preliminary results are then reported in Section 3 with experiments that use the same dataset as that in [8]. The paper is concluded with an overall discussion in Section 4.

2 2D Continuous Wavelet Transform for Surface Flatness Analysis

The Wavelet Transform is a signal analysis method that is based on the convolution of the input signal with a wavelet function at different locations along the signal and at multiple scales. This enables the detection of the signal pattern of the wavelet function at potentially any scale and at any location. Wavelets take their name from the fact that their energy is contained within a short period, and they typically have one main center frequency f_c. Therefore, the convolution of the wavelet at multiple scales and locations along the input signal can be used not just to detect the type of pattern represented by the wavelet, but to detect specific frequencies [13]. The Continuous Wavelet Transform (CWT) is one of the several variants of the Wavelet Transform that is commonly considered for pattern/frequency detection in a signal (the pattern/frequency being that of the selected wavelet). As previously shown by the authors in [8] and also [3], the CWT is well-suited to the problem of surface waviness characterization. An interesting property of the CWT (WT in general) is that it is applicable not just to a 1D signal, but also to 2D signals (and signals of higher dimension) [13].

Applying the CWT, like any other WT, requires the selection of the mother wavelet. One common CWT wavelet is the Mexican Hat wavelet. As show in 2D in Figure 2, this wavelet is composed of one main undulation with center frequency f_c that is the same for both dimensions. The center frequency of the Mexican Hat wavelet is f_c=0.252. By convolving an input 2D signal with the Mexican Hat wavelet at a given scale a, undulations of characteristic frequency f can be detected; f is simply calculated as [13]:

$$f = \frac{f_c}{\delta_p a} \tag{1}$$

where δ_p is the point sampling period in the input signal along the given dimension.

Table 1 gives examples of wavelengths which the CWT will respond to when applying the Mexican Hat to a signal with point sampling period δ_p=1cm for 10 different scales a. The last column shows the five k levels evaluated in the Waviness Index method that correspond to each scale a.

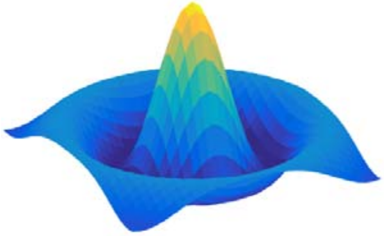

Figure 2: 3D view of the 2D Mexican Hat wavelet.

Table 1: Characteristic frequency *f* and corresponding wavelength $\boldsymbol{\lambda}$ at which the CWT responds when applying the Mexican Hat to a signal with point sampling period δ_p=1cm for 10 different scales *a*.

$\boldsymbol{a}$	$\boldsymbol{f}$ [cm^{-1}]	$\boldsymbol{\lambda}$ [cm]	$\boldsymbol{k}$
7.5	0.034	29.8	
15	0.017	59.5	1
22.5	0.011	89.3	
30	0.0084	119	2
37.5	0.0067	148.5	
45	0.0056	178.6	3
52.5	0.0048	208.3	
60	0.0042	238.1	4
67.5	0.0037	267.9	
75	0.0034	297.6	5

The results obtained using the 2D CWT analysis are typically presented in the form of a 3D *scalogram*, showing the CWT responses at each sampled point *(x,y)* on the 2D surface and each characteristic frequency *f* (i.e. scale *a*), as shown in Figure 3.

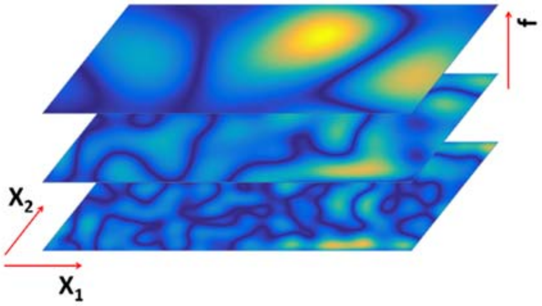

Figure 3. Scalograms for different values of characteristic frequency *f*.

By sampling TLS point clouds of a floor into a 2D grid with grid cell size δ_p, the 2D CWT can be applied to that transformed dataset to detect and precisely locate on the floor 'bumps' with a wide range of wavelengths. This is demonstrated with the experimental results shown in Section 4.

3 Proposed Method

A general overview of the method presented in this paper is shown in Figure 4. This method has four steps detailed in the following.

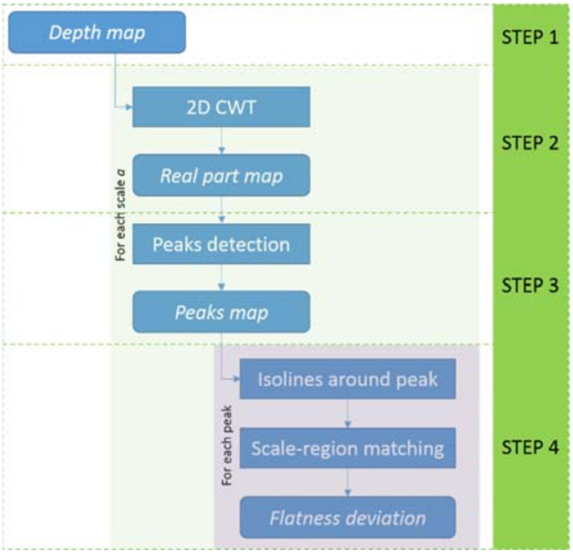

Figure 4. Overview of the method.

- Step 1: The point cloud obtained by means of the TLS device is pre-processed in order to segment the data corresponding to the floor. This data can then be processed as a *depth map*, by using a regular sampling δ_p of the slab surface (here we use δ_p=1cm) and associating to each sample the mean distance of the set of cloud points that can be locally associated to that sample location. Note that this process can be conducted automatically using scan-vs-BIM methods, as suggested in [14] [15] [16].
- Step 2 (Figure 3): The 2D CWT is applied to the depth map for each scale *a* of interest. This leads to the generation of a 3D scalogram, such as those shown in Figure 3, containing the CWT responses.
- Step 3 (Figure 5): For each 2D CWT scalogram obtained for each scale *a* of interest (Figure 5a), the peak responses (local maxima) are first detected, and peaks with values below 10% of the value of the maximum peak are filtered to remove 'noise' and non-critical responses (Figure 5b). Next, the closed *CWT response isolines* (i.e. connected sets of pixels with the same CWT response) that surround each detected peak are retrieved (Figure 5c) and the smallest ellipse that encloses the area defined by each isoline is calculated (Figure 5d).
- Step 4 (Figure 6): The lengths of the two main axes of each ellipse are calculated (Figure 6a). If any of

the two axes matches within ±1cm the wavelength $\boldsymbol{\lambda}$ corresponding to the scale a at which the CWT is applied, a flatness deviation is considered to be detected in that region for that wavelength (Figure 6b).

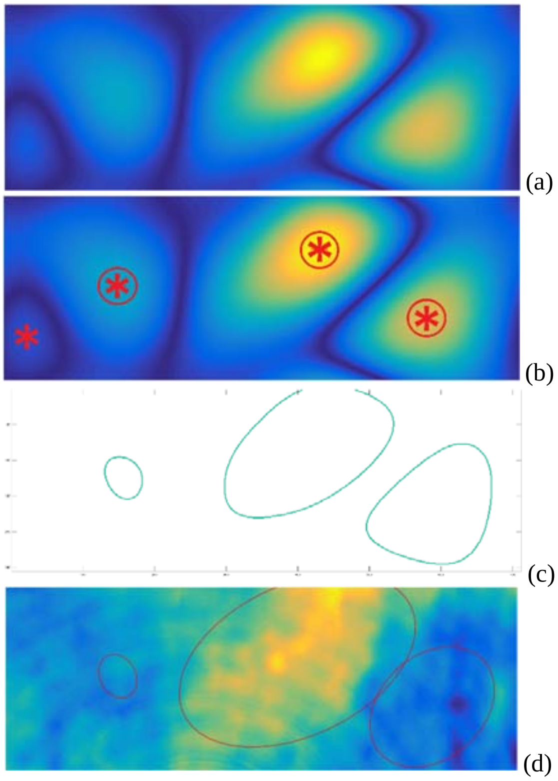

Figure 5. Step 3 of the process carried out for the detection of potential defects in a slab with $\boldsymbol{\lambda}$=297.6cm (i.e. a =75).

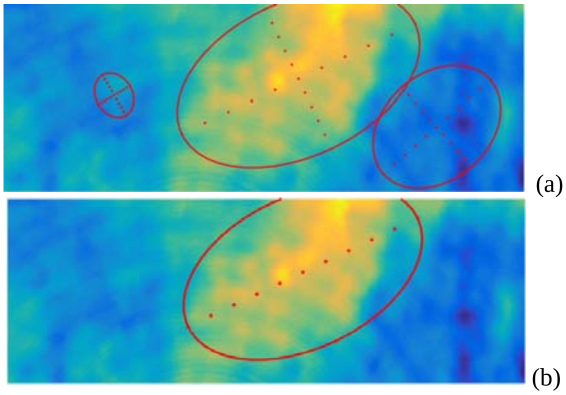

Figure 6. Step 4 of the process carried out for the detection of potential defects in a slab with $\boldsymbol{\lambda}$=297.6cm (i.e. a =75).

4 Experimental Results

4.1 Dataset

A first set of experiments have been carried out using the concrete floor slab of the Drainage Lab of the School of Energy, Geoscience, Infrastructure and Society at Heriot-Watt University whose dimensions are 2.75m x 7.25m. This slab is shown in Figure 7 and was already used in [8].

For the data acquisition, a Faro Focus 3D TLS was used. The final point cloud for the slab section of interest contained approx. 200,000 points (see Figure 8). As illustrated in Figure 8, the slab presents important deviations: the difference between the maximum and minimum height is 14 mm.

Figure 7. Drainage Lab slab studied in this work.

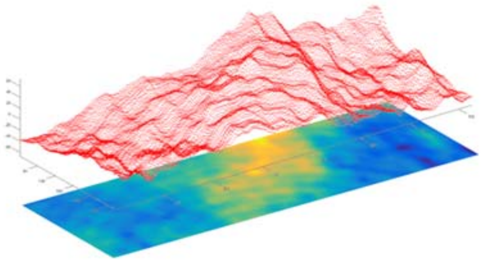

Figure 8. Point cloud and depth map of the Drainage Lab slab. Note that in this figure, the vertical axis presenting the point cloud elevation has been magnified to highlight the floor waviness.

4.2 Results

Figure 9 shows, enclosed by ellipses, the areas in which potential defects are found by the proposed method for the five wavelengths: 60, 120, 180, 240 and

300 cm (we show these wavelength because we later compare those results with those obtained with the Waviness Index method). For each ellipse, the axis with length similar to the studied wavelength, is plotted to illustrate the main direction of the detect planarity deviation. Note that no potential deviation is found for the λ=180 cm.

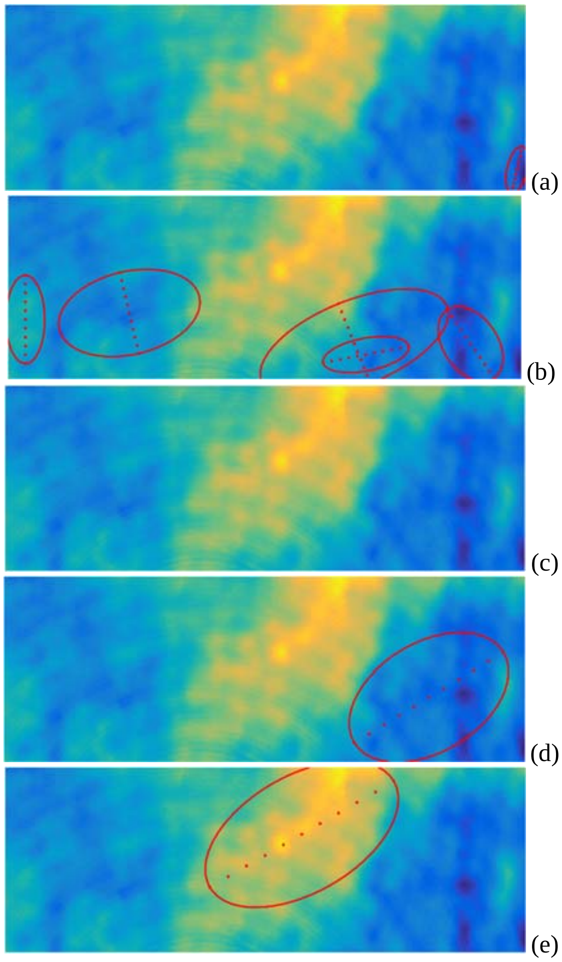

Figure 9. Potential deviations found for (a) 60, (b) 120, (c) 180, (d) 240 and (e) 300cm.

As shown in the previous images, several areas of deviation have been identified in the depth map of the slab for the considered wavelength. In previous works [7], this information had to be extracted from the scalogram by the reader in a manual manner. This task, which is time consuming and somehow complex, is now done completely automatically by the proposed new approach. This makes the whole process faster and more effective.

Figure 10 visually summarises the detected planar deviations for a study considering a continuous range of wavelengths between 60cm and 300cm. That information easily communicates to ground crews where planarity correction actions should be taken.

4.3 Comparison of with Waviness Index

Considering the Waviness Index (WI) method as the current state-of-the-art method, a comparison between WI and the proposed 2D CWT method is carried out.

Following the WI procedure specified in the standard ASTM-E1486 [7], survey lines are defined in directions parallel to the principal axes of the surface. Along these lines, survey points are defined every 30 cm and their elevation is measured. Then, the WI response [7] for each of the five levels k, corresponding to the wavelengths 60, 120, 180, 240 and 300 cm, is calculated using the equation:

$$LAD_k = \sqrt{\frac{\sum_{i=1}^{imax} LAD^2{}_{k,i}}{imax_k}} \qquad (2)$$

where $LAD_{k,i}$ is the WI response at the level k at the i^{th} evaluated location along the survey lines. The coefficient $imax_k$ is the number of locations where the response has been calculated at level k.

A comparable metric CWT_a is calculated to evaluate the 2D CWT response at each point evaluated at scale a. These values correspond to the previously mentioned LAD_k and are calculated as follows:

$$CWT_a = \sqrt{\frac{\sum_{j=1}^{jmax} CWT^2_{a,j}}{jmax_a}} \qquad (3)$$

where $CWT_{a,j}$ is the 2D CWT response at the scale a at the j^{th} sample location on the surface. The coefficient $jmax_a$ is the number of locations where the response has been calculated at scale a.

If the 2D CWT works well, then it would be expected that its response correlated with that of the WI method when for comparable scales a and levels k (i.e. the same wavelength), as defined in Table 1. Figure 11 shows the four points (CWT_a, LAD_k) obtained for the wavelengths 60, 120, 180 and 240cm (the slab is actually too small to assess the wavelength 300cm). Although it is hard to draw a full conclusion, the results show a remarkably strong correlation between CWT_a and LAD_k values, with R^2=0.9469. This result is supportive of the approach proposed here that can actually efficiently evaluated waviness with many more wavelength and can accurately report the location of where deviations are detected.

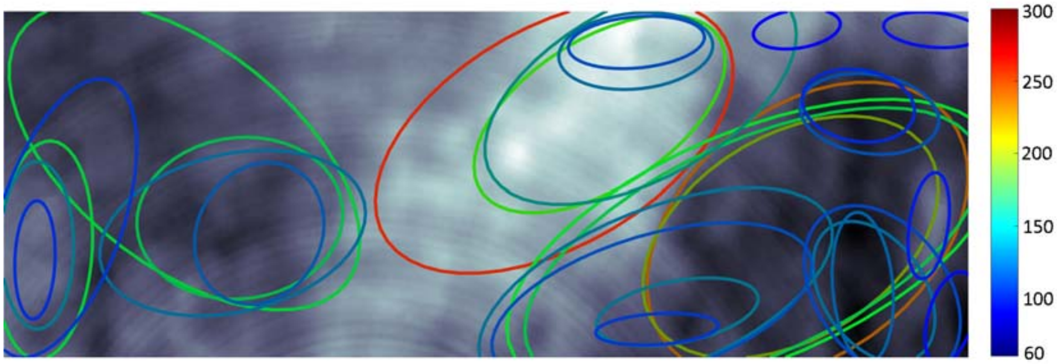

Figure 10. Map of defects for a continuous wavelength study from 60 to 300 cm.

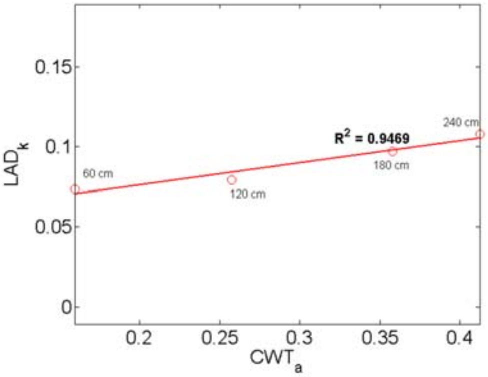

Figure 11: Correlation between LAD_k and CWT_a responses for each evaluated period.

5 Conclusions

The increasing use of TLS has revolutionized quality control in various industries. In construction, the capacity of TLS to deliver dense and accurate data from surfaces can greatly improve dimensional control in general, and flatness control particularly. Just like the introduction of profilometers has led to the emergence of the F-Numbers and Waviness Index methods (the current state of the art), the introduction of TLS offers an opportunity to review those methods once again and propose more robust and powerful ones.

The proposed 2D CWT approach makes full use of the density of measurements provided by TLS, and can assess waviness with levels of precision in the spatial and wavelength domains that more than surpass what was achievable with prior methods. The experimental results reported here positively demonstrate the potential value of the approach. Furthermore, a method is proposed to effectively detect deviations and communicates them effectively.

Nonetheless, the authors acknowledge that further work remains to be conducted to further validate the method. In particular, the authors will now acquire data from various slabs with various levels of specified flatness, ranging from housing foundation slabs to very flat slabs of industrial warehouses.

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