Flat and Level Analysis Tool (FLAT) for real-time automated segmentation and analysis of concrete slab point clouds

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Abstract -

In the United States, the flatness and levelness of concrete floors during construction is traditionally specified by a maximum allowable gap under a 3 meter straightedge. However, the straightedge method is inexact and rarely representative of the entire floor since the technician is free to choose any location on the floor to perform the measurement. In cases requiring a higher degree of precision and repeatability, concrete floor flatness and levelness can be measured using the standard test method ASTM E1155. With the recent introduction of advanced surveying instruments such as robotic theodolites and terrestrial laser scanners (TLS), the means now exist to modernize and expedite the measurement of floor flatness and levelness. This paper details the development and demonstration of a digital tool, named the Flat and Level Analysis Tool (FLAT), to automate and expedite the segmentation and analysis of flatness and levelness from dense point cloud data of concrete floor slabs. Segmentation algorithms were developed using unsupervised machine learning to extract the set of points belonging to the concrete floor slab from a full 360° scan of a construction site. After segmentation, automated analysis algorithms report the results according to the standard method. The developed algorithms were demonstrated on a dense point cloud captured from a concrete slab-on-grade at a construction site. Results show that the digital tool can quickly provide estimates for floor flatness and levelness with minimal human involvement with comparable accuracy to manual methods.

Keywords -

concrete floor, flatness, levelness, automation, real-time

1 Introduction

In the United States, the flatness and levelness of concrete floors during construction is traditionally specified by a maximum allowable gap under a 3 meter straightedge. For example, when a 3 meter straightedge is placed on the floor, a technician may measure a maximum distance of 6 mm between the floor and straightedge at any point for the floor to be considered acceptable construction quality (a specified flatness of 6 mm in 3 meters). However, the straightedge method is inexact and rarely representative of the entire floor since the technician is free to choose any location on the floor to perform the measurement. Additionally, this practice is not typically controlled using a standard method and results may significantly vary based on technician, tools, and methods.

In cases requiring a higher degree of precision and repeatability, concrete floor flatness and levelness can be measured using the standard test method ASTM E1155 [1]. This standard method specifies the means to extract and analyze data from a constructed floor to determine floor flatness F_F and floor levelness F_L numbers. Additionally, for concrete floors, ACI 302.1 specifies acceptable ranges for F_F and F_L [2]. Different building applications require varying degrees of F_F and F_L. For example, a warehouse with high-stacking shelves requires a high degree of both F_F and F_L to ensure a small risk of storage shelves overturning.

Even in the modern age of construction, the methods and equipment used to measure F_F and F_L are largely the same since the 1970s. With the recent introduction of advanced surveying instruments such as robotic theodolites and terrestrial laser scanners (TLS), the means now exist to modernize and expedite such measurements. For example, modern commercial software eases the analysis of 3D point clouds for flatness and levelness [3]. However, the process does not perform automated, real-time analysis. Instead, an experienced user is required to collect, analyze, and report the data. Fully automated procedures to analyze floor flatness and levelness would allow real-time assessment and lower the user skill requirement for assessment.

This paper details the development and demonstration of the Flat and Level Analysis Tool (FLAT), a digital tool to automate and expedite the segmentation and analysis of flatness and levelness from dense point cloud data of concrete floor slabs. Segmentation algorithms were developed

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using unsupervised ML to extract the set of points belonging to the concrete floor slab from a full 360 ° scan of a construction site. After segmentation, automated analysis algorithms report F_F and F_L according to ASTM E1155.

1.1 Floor flatness and levelness control

Floor flatness (F_F) and levelness (F_L) numbers are quantitative measures of a floor's smoothness and levelness [4]. In general, floor flatness is a measure of the local smoothness of the floor. F_F is a function of the change in floor elevation between colinear points spaced at 60 cm increments. The flatness of the floor affects the installation of flooring, ride quality, safety, and drainage. On the other hand, the floor levelness number is a global measure of the levelness of the floor. F_L is a function of the change in floor elevation between colinear points spaced at 3 m increments. The floor's levelness can impact drainage as well as the placement and design of shelves. Many types of buildings require a high degree of flatness and levelness such as warehouses with stacking shelves, ice rinks, and movie studios.

In the United States, the traditional method of consistent measurement of concrete floor flatness and levelness is the ASTM E1155 standard. This standard procedure consists of subdividing the floor slab into test sections, marking sample measurement lines, collecting measurements every 30 cm, and calculating F_F and F_L along each line, each aggregate test section, and the entire floor slab. ACI 302.1 specifies acceptable ranges for F_F and F_L based on the building use case. Specified values for F_F and F_L range from 15 to 50 for most applications. For example, where flatness and levelness are noncritical such as mechanical rooms and nonpublic areas, local values of 15 F_F and 10 F_L and overall values of 20 F_F and 15 F_L are acceptable. However, for applications requiring a high degree of flatness and levelness such as movie studios, local values of 35 F_F/F_L and overall values of 50 F_F/F_L are required at the minimum.

The procedure to gather data to calculate F_F and F_L is manually time-consuming. While the standard does allow the use of manual instruments such as straightedges, laser levels, and taut level wires to measure change in elevation, the fastest measurement tools allowed by the standard are inclinometers or profilometers. These instruments are "walked" or rolled along the surface of the slab to measure the change in elevation between two points spaced apart by 30 cm. Depending on the size and complexity of the slab, it may be necessary to collect 200 or more data points using these instruments. After data collection, analysis must be conducted to determine F_F and F_L from the acquired data. The entire process can take anywhere from 2 - 12 hours depending on the size and complexity of the concrete slab. In most cases, the process is not fast enough to identify issues in real-time to correct mistakes. Additionally, the measurement process itself cannot be completed on concrete before setting because the operator must stand on the concrete. Modern surveying instruments have the potential to complete the same data collection procedures in a fraction of the time and enable real-time validation while the concrete is still workable such that errors in flatness can be corrected more easily.

When issues with flatness and levelness are detected by traditional methods, the concrete has already hardened. Additional testing must often be conducted to determine where exactly the flatness or levelness issues are located. After locating the issues, remediation efforts typically consist of grinding, planing, surface repair, re-topping, or removal and replacement [4]. These efforts are costly and time-consuming to the concrete contractor. Additionally, the concrete placement contract often stipulates that if flatness and levelness specifications are not met on the first attempt, a reduction in payment will occur. Thus, concrete contractors have a major interest in identifying flatness and levelness issues in real-time such that costly mistakes can be corrected while the concrete is still workable.

1.2 Laser scanning and point cloud segmentation

Recent developments in advanced surveying instruments have yielded simple, easy-to-use laser scanning devices that can measure more than 2 million points per second at large distances. These modern instruments have the potential to significantly expedite the calculation of F_F and F_L for concrete slabs. Modern instruments are accurate at long ranges with peak range accuracy of 2 mm + 2 ppm or better. With continued development, these instruments are also becoming more affordable and accessible with easy-to-use interfaces. Additionally, most modern laser scanners come prepackaged with software to automate and simplify the process of registering multiple scans into a single frame; a process which can require several man-hours of effort from an experienced surveyor. As a result, laser scanners have the potential to easily replace handheld measurement devices such as the inclinometers and profilometers that are used to measure F_F and F_L.

However, one aspect of laser scanning that currently limits adoption is segmentation. Because scanners operate by spinning a mirror or aperture and rotating, the fastest method of scanning a site/object using a TLS is usually performing a full 360° scan. During this process, the scanner measures every object in sight. After completion, the operator must import the data into software to separate the points belonging to the object of interest (the concrete slab) from the rest of the points. This process is called segmentation. One of the major topics of research in construction automation is the automated segmentation of points clouds for varying applications [5, 6]. In particular, automated point cloud segmentation techniques exist to perform tasks ranging from automated digital twin generation [7] to prefabricated tolerance compliance assessment [8]. By automating the segmentation process using artificial intelligence, the process can be turned from a several-hour manual process into a few second-long automated process, increasing the accessibility of laser scanning technologies to a wider array of applications and users.

2 Methodology

The primary research of this work details the development of (1) an automated segmentation algorithm for concrete slabs and (2) an automated analysis algorithm to perform and report on F_F and F_L following the ASTM E1155 standard. Other research efforts have focused on the development of methods to automate the process of flatness and levelness quality control for concrete slabs [9, 10, 11, 12]. However, no work exists to the authors' knowledge that combines both model-free automatic segmentation and automatic analysis of F_F and F_L according to ASTM E1155. The proposed methods were developed to automatically segment a concrete slab with no user interaction from a 360° dense point cloud and generate F_F and F_L according to ASTM E1155.

2.1 Segmentation

The automated segmentation of points belonging to the concrete slab is necessary to automate the analysis. The segmentation process must fully isolate the points belonging to the slab from the remainder of the point cloud data. Concrete slabs can be separated into two types: slabs on-grade and suspended slabs. Concrete slabs on-grade are simply constructed to bear directly on foundations and the soil beneath. Suspended slabs are constructed in multi-story buildings at elevations above the ground. Suspended slabs are significantly more difficult to construct in conformance with stringent flatness and levelness requirements. For both types of floor slabs, the slab is usually constructed before the walls which presents a specific segmentation issue. For full 360° scans, the entire construction site is included in the point cloud. For suspended slabs, the scanner will capture the floor on which it is set and the structure above in multi-story constructions. As a result, the automated algorithm must be able to identify what points belong to the floor slab to analyze with potentially multiple near-planar surfaces existing in the point cloud data.

The proposed segmentation algorithm consists of several steps to isolate the points belonging to the concrete slab. Figure 1 illustrates the procedure. Each step in the procedure will be further discussed in more detail.

The first step in the analysis is to reduce the data in the point cloud so that the subsequent steps can be completed more quickly. The goal is to reduce the data by at least 95%; however, the actual reduction will depend on several factors including the original point density and scan area. Data reduction is achieved by voxel-downsampling [13]. The process of voxel-downsampling generates a grid of cubes of specified dimension. Within each cube, all points are averaged, and the resulting voxel is reduced to a single point located at the mean. For this work, a voxel size of 5 cm was determined to be effective in reducing the point cloud while still accurately providing enough data for the remaining steps in the procedure.

Next, plane segmentation is performed using a random sample consensus (RANSAC) procedure [13] with some modifications. This modified RANSAC is performed to identify the near-level plane of the concrete slab. The procedure iteratively selects three points in the cloud to generate a plane. Valid points must be below the origin of the point cloud (which is the location of the scanner) to ensure that the identified plane is the intended plane of the floor. A distance threshold specifies the normal distance from the plane that points are selected as inliers. A modification to the procedure eliminates planes that are not within a specified threshold of level (i.e. for the plane described by $z = ax + by + c$ where z is elevation, the parameters a and b must be within a specified threshold close to zero). After a fixed number of iterations, the plane with the largest number of inlier points is returned as the plane representing the concrete slab.

The points identified by the modified RANSAC frequently include scattered miscellaneous points that do not belong to the concrete slab's point cloud. Such outliers belong to parts of the surrounding area that fall within the plane of the slab. Because the slab is often slightly elevated from the adjacent soil, a gap most likely exists between the point cloud of the slab and the other planar outlier points. A density-based scan (DBSCAN) clustering method [13, 14] is performed to identify the largest cluster of points which belong to the concrete slab.

After the slab is isolated, a principal component analysis (PCA) [15] is conducted to align the edges of the slab to the major axes. Before conducting PCA, the points are projected to the xy-plane, removing the elevation, (z) axis. The PCA determines the first primary component of the points. The points are then rotated by the angle between the first primary component vector and the x-axis, aligning the slab with the major axes.

After alignment, edge optimization is performed to cleanly delineate the edge of the slab from miscellaneous features. Although the standard procedure requires that measurements must be sufficiently far from the slab edges, this process is necessary due to the possibility of miscellaneous features near the slab edges which could affect the

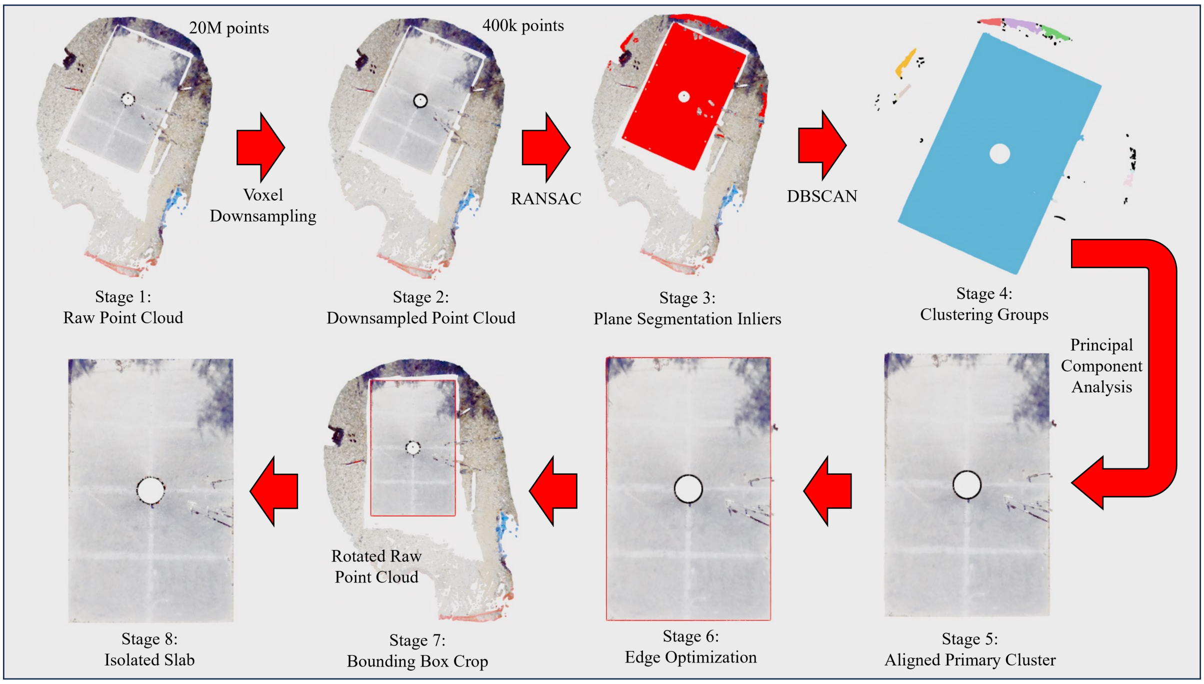

Figure 1. Workflow for automated segmentation of concrete slab.

automated analysis algorithm if not removed. The edge optimization is completed in the xy-plane. The median (M) and median absolute deviation (MAD) are calculated for all points projected onto the xy-plane. All points p are normalized according to $n = (p - M)/\text{MAD}$. Consider the probability density function (PDF) of the normalized points on each axis, then the inlier points satisfy $|\text{PDF}(n_x)| < \alpha$ and $|\text{PDF}(n_y)| < \beta$, where α and β are specified thresholds. A bounding box is generated for the inlier points. Points falling outside of the bounding box are not considered part of the automated analysis, as shown in Figure 2.

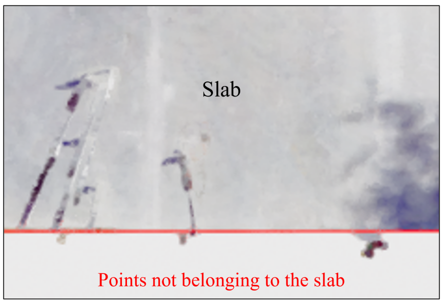

Figure 2. Edge optimization for trimming miscellaneous points.

The bounding box generated from edge optimization is used to crop the slab from the original point set before voxel downsampling, rotated by the same angle determined by the PCA. The points inside the bounding box are the resulting point cloud which includes only the isolated points belonging to the concrete slab. It is important to note that the bounding box is used to crop the original, raw point cloud before voxel-downsampling was performed which retains the original accuracy of the collected point cloud. Finally, the origin is set to the most negative point within the cloud of the isolated concrete slab. After this step, the resulting point cloud is ready for the automated analysis.

2.2 Analysis

After segmenting the point cloud to yield only the points belonging to the concrete slab, an analysis can be performed to automatically generate F_F and F_L according to ASTM E1155. As part of the measurement procedure of ASTM E1155, a series of lines are established from which to measure elevation changes every 12 inches (≈0.3 m).

There are several rules for conducting the setup of measurement lines according to the standard method. Some general requirements apply to the overall procedure. No portion of the entire test surface can be associated with more than one test section, and no test section boundary should cross any construction joint. Other standard requirements are described where appropriate during the algorithm descriptions.

Because the points belonging to the slab are segmented in the prior step, many of these criteria can be tested as part of the algorithm. First, the minimum and maximum bounds of the concrete slab are extracted from the point cloud by the minimal oriented bounding box. From these bounds, the slab dimensions are extracted, and the slab area can be calculated. The slab dimensions and area are checked against the approval criteria of ASTM E1155 (i.e., the test section cannot measure less than 8 ft (2.4 meters) on a side and the test section cannot have an area less than $320\,\text{ft}^2$ ($29.7\,\text{m}^2$). If the slab is large enough, the algorithm is allowed to proceed.

The standard procedure also requires that no part of any sample measurement line fall within 2 ft (≈0.61 m) of any slab boundary, construction joint, isolation joint, block-out joint, penetration, or other similar discontinuity. However, two exceptions are provided. First, shrinkage crack control joints formed by either partial depth sawcuts or by partial depth inserts can be ignored. Second, if the area to be excluded from the measurement exceeds 25% of the test section area, then the 2 ft (≈0.61 m) boundary exclusion does not apply. The boundary exclusion area is calculated and tested to determine if it exceeds 25% of the test area. If the boundary exclusion area is not too large, then the allowable sample measurement area is inset within the slab perimeter; otherwise, the entire surface area of the slab is treated as the allowable sample measurement area.

The standard methods provide conditions for sample measurement lines within each test section. Each line must be arranged to blind the test results by using one of two methods: (1) orienting all lines at 45° to the longest construction joint abutting the test section, or (2) placing equal numbers of lines of equal aggregate length both parallel to and perpendicular to the longest test section boundary. However, when the short dimension of the slab being measured is less than 25 ft (7.62 m), all measurement lines must be 45° diagonals. Sample measurement line generation criteria allow lines to be placed at ±45° to the longest construction joint regardless of slab dimensions. For this reason, the automated analysis procedure will always generate measurement lines at 45° diagonal to the longest dimension of the slab. As a reminder, the most negative point on the slab was set as the origin for the local slab coordinate system before automated analysis. Because the largest slab dimension is aligned with the x-axis as part of the automated segmentation, each measurement line can be described by the slope-intercept formula, $y = mx + b$, where x, y are the coordinates of a point along the line, m is the slope which is either -1 or 1, and b is the y-intercept which will vary in uniform spacing to create lines that span across the entirety of the allowable sample measurement area.

A series of lines are constructed to fill the area that is generated from doubling the slab width and height. Points are generated along each line, spaced at 12 inches (30.48 cm). Adjacent parallel lines are separated by a perpendicular distance of 4 ft (1.22 m) as required by the standard procedure. The construction of these lines and measurement points are illustrated in Figure 3. Lines are constructed at angles of $-45°$ and 45° from the x-axis (which is aligned with the longest dimension of the slab). Lines are trimmed such that all points fall within the allowable sample measurement area. The length of each line is calculated by determining the Euclidean distance between the start and end points. The standard procedure requires that no sample measurement line measure less than 11 ft (3.35 m). If any line is shorter than the allowable 11 ft (3.35 m), then the line is removed from the sample set. Additionally, at the end of this step, the total number of sample measurement points is determined according to the standard calculations. The standard method details that a minimum number of readings is required per test section conforming to the following equations: $N_{\min} = 2\sqrt{A}$ for $320 \leq A \leq 1600$ or $N_{\min} = A/30$ for $A > 1600$ where A is the test section area in square feet. If $N_{\min}$ is larger than the actual number of sampled points, the test results will be deemed invalid and not reported; otherwise, the algorithm is allowed to proceed.

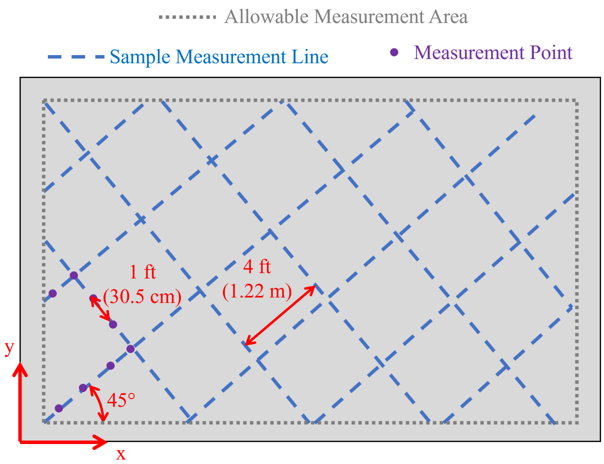

Figure 3. Automated sample generation.

After sample line generation, the next step in the algorithm is to iterate over each point within each line to determine the closest point in the slab point cloud from which to extract the height measurement. First, a kd-tree is generated for the slab point cloud projected to the xy-plane [16]. The kd-tree is queried with each point along a sample measurement line, also projected to the xy-plane, to determine the nearest neighbor within the slab point cloud ignoring the elevation (z-axis). The elevation, z-component, of the nearest neighbor in the slab point cloud is recorded as the measured sample height of the queried point of the sample measurement line. This process is repeated iteratively for each point along each sample measurement line. The result is the recorded elevations of the slab every 12 inches (30.48 cm) along the sample measurement lines. After the collection of slab elevations along each measurement line, the analyses detailed by ASTM E1155 [1] are performed to determine F_F and F_L for each sample measurement line and the overall slab (hereby referred to as composite). In summary, floor flatness is a function of the standard deviation of curvature of difference in elevation between points separated by 24 inches (60.96 cm). Floor levelness is a function of the standard deviation of curvature of difference in elevation between points separated by 10 ft (3.048 m). Composite floor flatness and composite floor levelness numbers are calculated by iteratively combining floor flatness or levelness numbers for each sample measurement line weighted by the number of samples. The reader is referred to the ASTM E1155 standard for complete details on how F_F and F_L are calculated [1].

2.3 Limitations

As is, the automated segmentation and analysis algorithms include some limitations. First, both algorithms assume that the concrete slab is rectangular. For complex shapes beyond rectangles, the edge optimization process fails to cleanly extract the edge of the slab. Additionally, the automated segmentation algorithm assumes that the slab is subdivided into a single test area. If construction joints are present, according to ASTM E1155, the slab must be subdivided into multiple test areas. This subdivision process is currently not automated within the algorithm. Moreover, if the slab includes multiple elevations (there are steps in elevation), then the automated analysis will only identify a single elevation. In future work, these limitations are planned to be addressed to allow the automated segmentation to analyze multiple elevations and multiple combinations of rectangular slab areas.

3 Demonstration

The automated segmentation and analysis algorithms were tested on an actual concrete slab located on the Oak Ridge National Laboratory site. A concrete slab-on-grade with design dimensions of 80 ft (24.4 m) by 50 ft (15.2 m) was scanned within 7 days of concrete placement. The slab was designed to be noncritical in terms of flatness and levelness requirements; as a result, flatness and levelness numbers were expected to be on the low end. A Leica MS60 was placed near the center of the concrete slab and set to scan the entire surrounding area using a full-dome scan setting with a maximum point resolution of 3 mm at the furthest edge of the slab. All scanned points within the perimeter of the concrete slab had a point spacing of less than 3 mm. The laser scan included the full 360° view of the construction site. Figure 4 shows the raw .pcd file of the scan that was loaded into the FLAT digital tool.

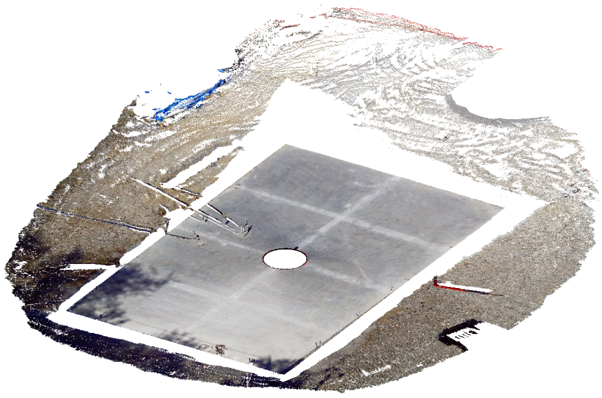

Figure 4. A portion of the full-dome scan of the construction site with concrete slab.

The automated segmentation and analysis algorithms of FLAT were written in Python. The automated procedures use several input parameters to perform various functions. Table 1 shows the parameters used in the demonstration. Voxel Size is the dimension of the voxel cube used for downsampling. The Plane Distance Threshold is the minimum normal distance between the RANSAC plane and points to be considered as inliers. Cluster Neighbor Radius is the maximum distance between points to be considered members of the same cluster. Cluster Minimum Points is the minimum number of points that a cluster must contain. Because only the largest cluster is taken, this parameter has minimal effect on the overall algorithm. Edge Optimization Bin Size controls the size of bins used to generate the PDF(n_x) and PDF(n_y) for edge optimization. The peak accuracy of slab dimensions is the same as this specified parameter. The Edge Optimization Threshold is the minimum threshold (α and β) for the probability density function for a bin to be considered an inlier (part of the slab).

Table 1. Parameters for the demonstration.

Parameter	Value
Voxel Size	5 cm
Plane Distance Threshold	5 cm
Cluster Neighbor Radius	30 cm
Cluster Minimum Points	50
Edge Optimization Bin Size	3 mm
Edge Optimization Threshold	0.10

One proposed feature of the FLAT digital tool is the real-time evaluation of floor flatness and levelness which enables measurement and correction of flatness and levelness issues while concrete is still workable. For the MS60 used in this study, the single-view dense point cloud with

Table 2. Run times. 100 iterations.

Task	Run Times (sec)			
	Min	Max	Mean	Std
Downsample	1.03	1.60	1.17	0.11
Segment Plane	0.07	47.31	9.95	10.48
Cluster	0.92	1.71	1.17	0.11
Align	0.20	0.27	0.22	0.02
Optimize Edge	0.03	0.06	0.04	0.01
Crop	2.11	2.91	2.35	0.17
Generate	0.13	0.31	0.16	0.02
Measure	5.47	8.22	6.08	0.44
Calculate	0.001	0.02	0.002	0.002
Entire Procedure	10.63	58.21	21.13	10.51

a specified resolution was collected in approximately 30 minutes. However, many TLS boast faster scanning rates and can capture point cloud data with higher resolution in a fraction of the time. Initial running time targets for the automated segmentation and analysis of FLAT were proposed at 60 seconds per 1000 m^2 of slab area. Table 2 shows the running times for each task of the FLAT digital tool on a standard laptop computer. Tasks of the automated segmentation process include, in order, Downsample by voxel downsampling, Segment Plane by RANSAC level plane segmentation, Cluster by density-based scan (DBSCAN) clustering, Align by principal component analysis (PCA), Optimize Edge by the proposed method, and Crop the original point cloud using the minimal oriented bounding box determined from the algorithm. Tasks of the automated analysis process include, in order, Generate sample measurement lines according to ASTM E1155, Measure the elevation of the nearest neighbor point in the cloud to sample measurements, and Calculate floor flatness and levelness according to ASTM E1155.

The mean total run time was approximately 21 seconds. Considering the surface area of the slab (370.88 m^2), the resulting average run time is 56.6 seconds per 1000 m^2 of slab area. Most tasks within the algorithms have consistent run time except for RANSAC. This variability in execution time is expected due to the random nature of the procedure. One option to reduce the time of this procedure, which may be introduced in the future, is to change to plane fitting of three user-specified points. Although this change could reduce processing time variability and improve repeatability, the resulting algorithm would have vastly reduced autonomy.

The output of the algorithms was also assessed. Table 3 shows the output of algorithms for slab dimensions, composite flatness, and composite levelness for 100 iterations of the algorithm on the same dense point cloud. Composite flatness and composite levelness refer to the calculated value by joining all flatness and levelness numbers for all sample measurement lines. Of the 100 iterations, 5 yielded segmentation results that incorrectly identified the plane of the concrete slab surface resulting in a failure rate of 5%. The results of failed runs were not included in the statistical analysis of the output results.

Table 3. Reported output. 100 iterations.

Output	Value			
	Min	Max	Mean	Std
Slab Length (m)	24.258	24.553	24.419	0.025
Slab Width (m)	15.283	15.563	15.304	0.048
Composite F_F	5.3	8.2	7.0	0.61
Composite F_L	12.3	13.5	13.1	0.27

As shown among the 100 iterations, there is some variability in the output results. The processes within the algorithm that could induce the most variability include plane segmentation, clustering, and alignment because they use unsupervised machine learning methods which can produce differing results between iterations. Since these processes are stacked upon each other, the variability increases further. For example, for the slab dimensions, the range of extracted values is approximately 25 centimeters. Although this value is a small percentage of the overall dimensions, the variability in dimensional output is too large to accurately assess the slab's dimension with a single execution of the algorithm. Slab dimensional tolerances are commonly 0.75 in (19 mm) according to ACI 117-10 [17]. Ideally, the algorithm should produce results with variation less than this tolerance.

Additionally, there is variability in the output for floor flatness and floor levelness. Floor flatness numbers ranged from 5.3 to 8.2. This variability is hypothesized to occur within the plane segmentation, clustering, and edge optimization procedures. An intermediate step after plane segmentation where the user confirms that the slab has been correctly identified with near-perpendicular corners could help minimize variability between iterations. In future work, the source of variability will be addressed to reduce the range of output.

To determine the true values for composite floor flatness and floor levelness, ASTM E1155 was manually completed by extracting point elevations along sample measurement lines from the point cloud data gathered from the laser scan. Manually created sample measurement lines were created at similar locations as sample measurement lines automatically generated by the analysis algorithm. This manual analysis yielded a composite floor flatness of 7.6 and composite floor levelness of 14.1. In future work, the deviations between manual and automated method results will be investigated. The total run time of all 100 iterations was 35 minutes. Considering that 100 iterations of the analysis take 35 minutes, which is a significantly shorter amount of time compared to the traditional method, it is still reasonable for the digital tool to reduce the amount of time required to determine floor flatness and levelness with a high degree of accuracy. Future work will include a validation study to compare the digital tool output with conventional methods to perform ASTM E1155.

3.1 Discussion

A major finding of this study is that ASTM E1155 has several major shortcomings compared to modern surveying methods. Although the standard method has been clearly established for some time, it is not exhaustive even when optimized using automated procedures. The standard procedure limits the placement of sample measurement lines so that adjacent parallel lines are not closer than 4 ft (1.22 m). The purpose of this limitation in the standard is unclear to the authors and excludes a significant portion of the slab surface area from measurement, potentially hiding flatness defects. Modern surveying instruments can quickly capture sample elevations at high density (3 mm or more). A better alternative is to generate a topographic map of the slab topography to highlight the degree and locations of imperfections in flatness.

4 Conclusions and next steps

A Flat and Level Analysis Tool (FLAT) was developed to automate the process of determining floor flatness and levelness for concrete slabs according to ASTM E1155. An automated segmentation algorithm and automated analysis algorithm were developed and tested on a demonstration concrete slab on grade. Results of the demonstration of the algorithms show that the digital tool can quickly provide estimates for floor flatness and levelness with minimal human involvement.

In future work, FLAT will be optimized to minimize the variability of output results to ensure consistent output of slab dimensions and floor flatness/levelness numbers. Additionally, the automated segmentation limitations on slab shapes, dimensions, and complexity will be addressed to extend applicability to more types of concrete floors. The output results of FLAT must also be compared with standard output from conventional methods to perform ASTM E1155. Ultimately, additional point cloud data of different slabs must be collected to test the algorithms.

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