ONE-MM 3D LASER IMAGING SURVEY FOR COMPREHENSIVE RUNWAY EVALUATION

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ABSTRACT

Based on the application of 1mm 3D imaging technology for pavement survey, and through the use of inertial and other types of profiling devices, it is possible to establish a virtual runway with necessary x, y, and elevation accuracies for engineering analysis. A field example of such application is illustrated on a full-size runway that was surveyed in the spring of 2014 with the PaveVision3D technology of WayLink Systems Co., inertial profiling for longitudinal profiles, and an inclinometer based reference device for transverse profiling. The potential applications of a virtual runway include nearly all surface evaluations of runways, including longitudinal profiling for Boeing bumps, transverse profiling, grooving analysis, and various distresses. The most important application of a virtual runway is that complete surface of the runway at 1mm resolution is available to engineers who may choose to examine anywhere on the runway for defects and study remedial actions, now or later.

INTRODUCTION

Runway surface condition is a critical safety concern and part of pavement evaluation at airports. With the emerging 1mm 3D imaging technology for pavement survey (Wang 2011), and through the use of inertial and other types of profiling devices, it is possible to establish a virtual runway with necessary x, y, and elevation accuracies for airport runway surface analysis. Complete surface of the runway at 1mm resolution is available to engineers who may choose to examine anywhere on the runway for defects and study remedial actions. In the spring of 2014, a full size airport runway and taxiway surfaces are surveyed using the Digital Highway Data Vehicle (DHDV) equipped with the 1mm PaveVision3D Ultra (3D Ultra) laser imaging technology by WayLink Systems Co. The testing runway is newly constructed, 150 ft in width and 8,800 ft in length (marked in blue) as shown in Figure 1. One-mm surface data are also collected for all the five taxiways, approximately 100 ft wide by 800 ft long (marked in red) in Figure 1.

The collected 1mm 3D surface data can be used for all surface evaluations of runways, including longitudinal profiling for Boeing bumps, transverse profiling, grooving analysis, and various distresses. Specifically, in this paper the data collection and various data analysis of the 1mm 3D data collected at highway speed for both runway and taxiways are provided:

- 3D imaging of the runway and taxiways at 1mm resolution;
- PCI analysis for the runway;
- Longitudinal profiling analysis for the runway and taxiways;
- Runway grooving identification, measurement, and evaluation;
- Transverse profiling using SurPro 3500 walking profiler.

DATA COLLECTION

DHDV has been evolved into a sophisticated system to conduct full lane data collection on roadways at highway speed up to 60mph (about 100 km/h). With the latest PaveVision3D Ultra, the resolution of surface texture data in the vertical direction is about 0.3 mm and in the longitudinal direction is approximately 1 mm at data collection speed of 60MPH. Figure 2 shows the exterior appearance of the DHDV and the working principle of the PaveVision3D Ultra technology, which is able to acquire both 2D and 3D laser imaging data from pavement surface through two separate sensors. Recently, two 3D high resolution digital accelerometers have been installed on the DHDV, which allows DHDV to be capable of reporting compensated pavement surface profile and generating roughness indices such as International Roughness Index (IRI), and Boeing Bump Index (BBI). DHDV system can be equipped with a dual-point AMES high speed longitudinal profiler as well, which is setup to operate simultaneously with the PaveVision3D system. The data collection between the two systems is synchronized.

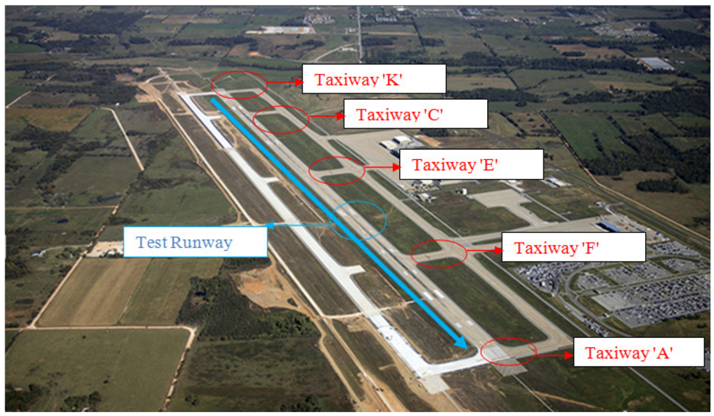


Figure 1 Airport Runway and Taxiways

Figure 2 DHDV Equipped with Pavevision3D

The SurPro 3500 Walking Profiler is a rolling profilometer-type profiling devices and can automatically collect runway unfiltered elevation profiles at speeds up to 4 km/h. SurPro elevation profiles are used as the reference profiling.

Both the runway and five taxiways have been surveyed using the DHDV vehicle equipped with 3D Ultra at highway speed. The data collected include 3D surface height data, 2D pavement surface intensity data, right of way (ROW) data, longitudinal and transverse profiling data. The 3D Ultra data are subsequently used to perform preliminary examination of runway surface, conduct PCI analysis, calculate longitudinal profiling indices, measure runway groove dimensions and evaluate groove performance.

Because one DHDV pass can only cover 4,096 mm in width, multiple runs are required to cover the entire extend of the runway or taxiways. It takes 16 longitudinal runs to survey the 8 slabs on the runway, two runs per each slab. In order to have full coverage of the entire runway, there are overlapped areas between two consecutive runs of data collection. The sequence of the 16 runs is illustrated in Figure 3. Similarly, multiple passes, ranging from 11 or 14, are performed to collect 3D Ultra data for taxiways. The first run of data collection starts from the Northeast corner of each runway and the last run ends at the Southeast. All passes begin from the east of each taxiway and finish at the west end.

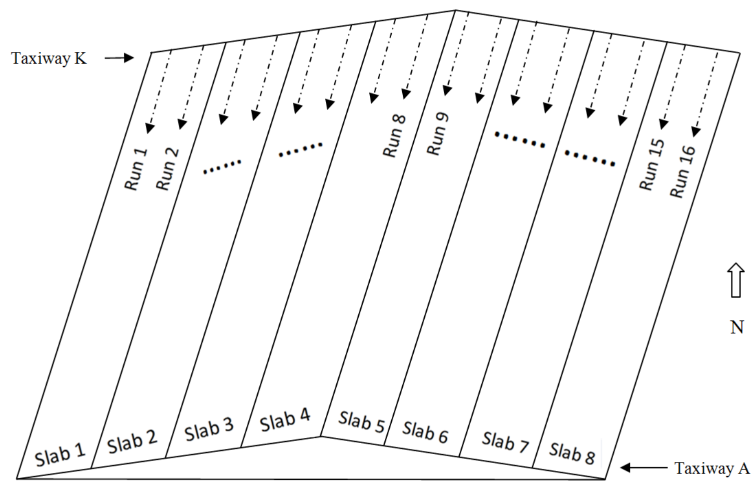


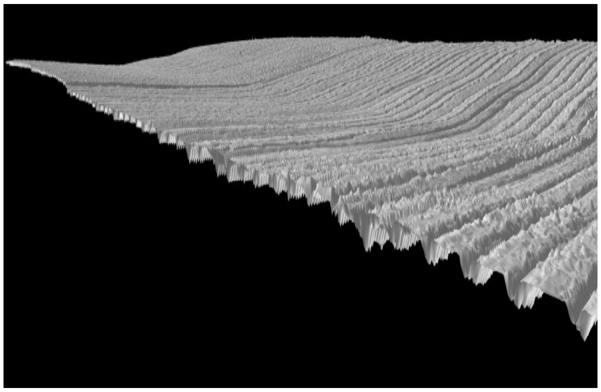
Figure 3 Sequence of Data Collection for Runway

Multiple SurPro3500 profile data are collected continuously along the runway and taxiways at both longitudinal and transverse directions. Longitudinal SurPro profiling data can be used for roughness analysis, while transverse profiling for cross slope measurement. There are two SurPro runs in the longitudinal direction on the runway keel: around 3 ft left and right of the runway centerline. The transverse SurPro runs on the runway are located at each runway edge light fixture. Three longitudinal SurPro runs are performed for each taxiway: one in the north half, one in the south half, and the other around the center of the taxiway.

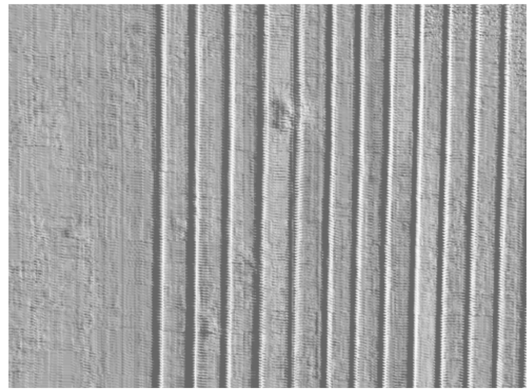
PRELIMINARY EXAMINATION OF RUNWAY SURFACE

The 1mm 3D runway surface data collected from DHDV can be visually viewed and examined for surface defects and specific construction problems. It is observed that the runway shows more surface problems starting from approximately reference station 6,000 to the south end of the runway. Due to time limitations, in this paper only the runway section from reference station 6,000 to the intersection of the runway with taxiway F is investigated aiming to capture the specific construction problems on the severe problem areas.

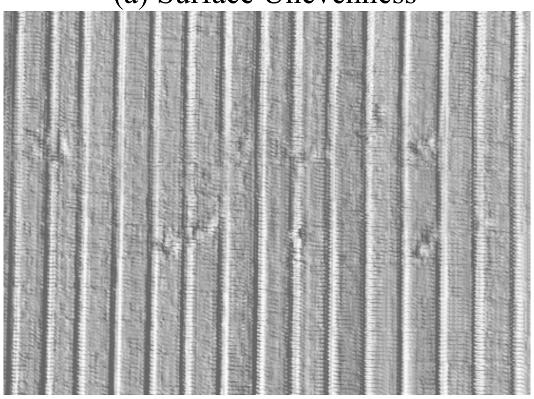
MHIS-3D Deluxe, a proprietary WayLink software designed to view and analyze collected DHDV data, is used for this purpose to examine each individual run of DHDV data. The data are saved by frames; each frame has a dimension of 2,048mm in length and 4,096mm in width. In total, there are 953 images involved in this extensive examination. There are primarily seven types of pavement surface defects on the runway: surface unevenness, popouts, joint spalling, faulting, scaling, excessive grinding, and grooving problems. Typical image for each defect type is shown in Figure 4. It is noted that some of the PCI defects don't reach the level of distress defined in the ASTM standard. In other words, this preliminary investigation is only approximate and not to fully ASTM standards.



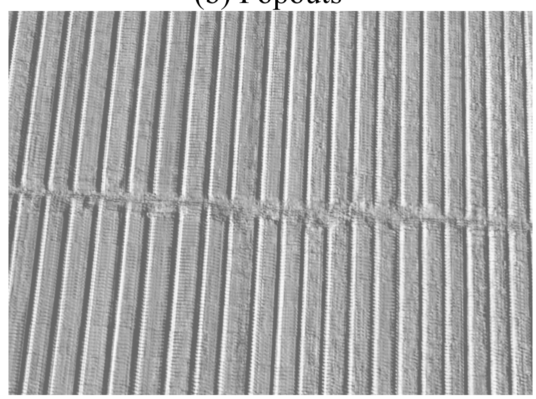
(a) Surface Unevenness



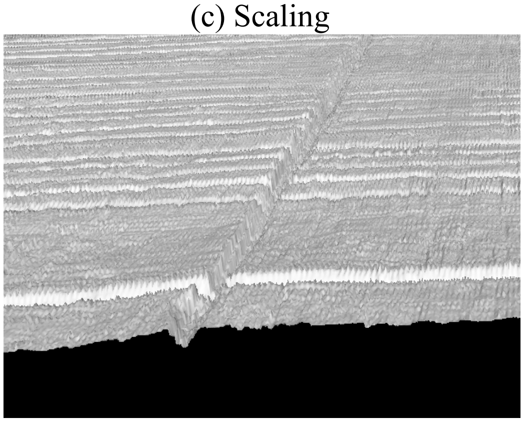
(b) Popouts



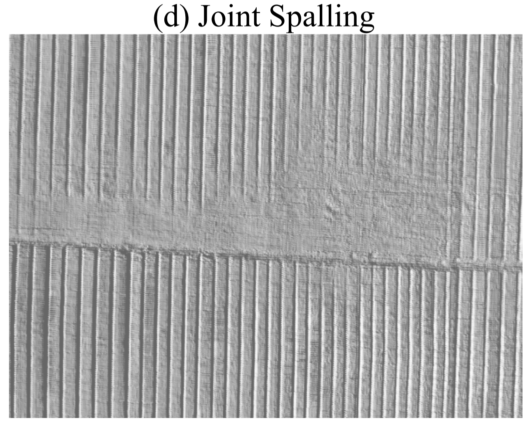
(c) Scaling



(d) Joint Spalling



(e) Faulting



(f) Excessive Grinding & Grooving Problems

Figure 4. Example Runway Surface Defects.

Subsequently, investigation is conducted frame by frame to identify surface defects. The number of frames with specific defect type is recorded and the percentage of frames that have defect(s) is calculated in Table 1. It can be seen that this section of the runway has extensive amount of popouts, surface unevenness, and moderate amount of joint spalling, faulting, scaling, excessive grinding. It should be noted that only missing grooves are counted in the preliminary examination. More detailed groove performance evaluation is provided later in this paper.

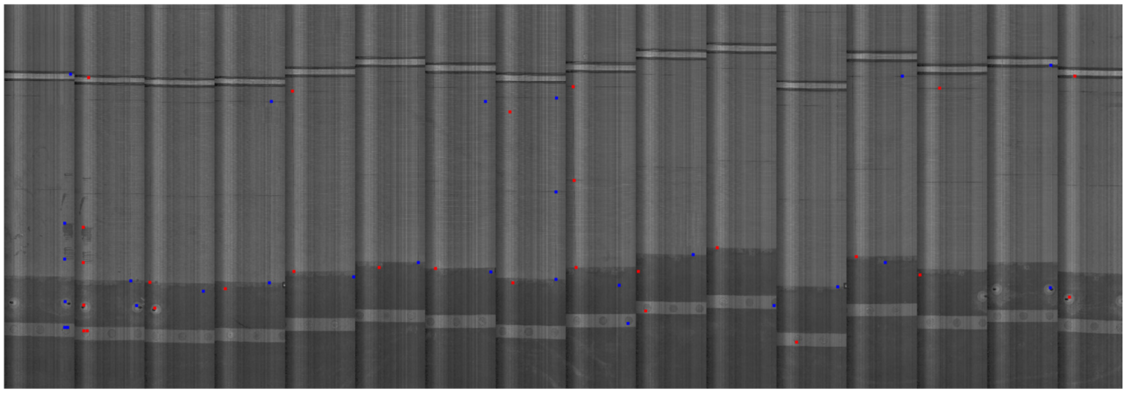
Table 1.
Surface Defects from Reference Station 6,000 ft to the Intersection with Taxiway E.

Surface Defect	Severity Level	# Frames With Defect (953 in total)	Percent Frames with Defect (%)	Total Frames with Defect (%)
Surface Unevenness	L	237	24.87	30.64
	M	26	2.73	
	H	29	3.04	
Popouts	L	397	41.66	42.60
	M	8	0.84	
	H	1	0.1	
Joint Spalling	L	155	16.26	16.78
	M	5	0.52	
	H	0	0	
Faulting	L	70	7.35	10.08
	T	26	2.73	
Scaling	L	112	11.75	11.96
	M	2	0.21	
	H	0	0	
Excessive Grinding	On Joints	65	6.82	18.78
	On Grooves	114	11.96	
Missing Grooves		13	1.36	1.36

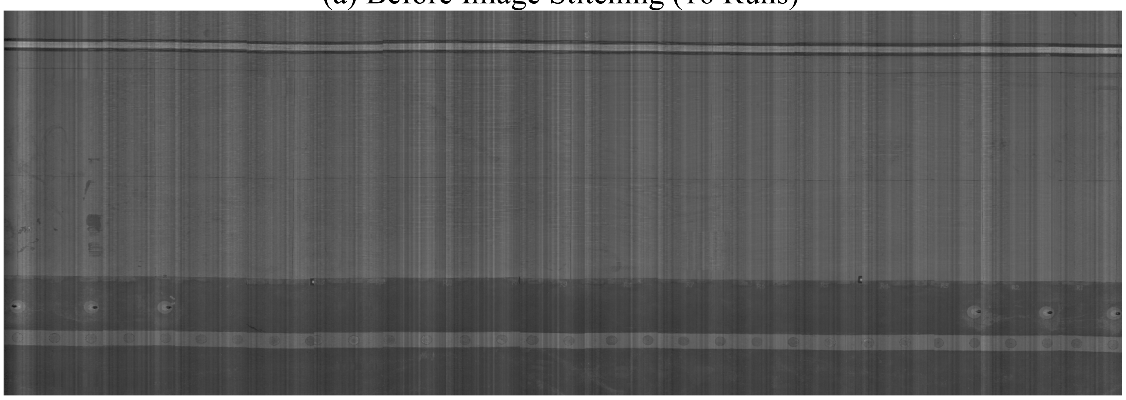
PCI ANALYSIS

The Pavement Condition Index (PCI) rating procedure was developed by the U.S. Army Corps of Engineers and is now widely used for airport runway and highway pavement as described in ASTM D5340 Standard Test Method for *Airport Pavement Condition Index Surveys*. The PCI is a numerical index, ranging from 0 for a failed pavement to 100 for a pavement in perfect condition. Deduct values are defined for each distress type and severity level based on deduct curves.

MHIS-Airport Deluxe was designed particularly for airport pavement analysis and coded based on ASTM D5340 standard (2011). Specifically, MHIS-Airport Deluxe has unique features designed and built to satisfy airport pavement PCI procedure for distress survey. Additionally, MHIS-Airport Deluxe software stitches images from multiple DHDV passes into one single virtual runway with 1-mm resolution, divides the runway into slabs and sample units for PCI analysis. Figure 5 shows the images before and after the stitching process. The red and blues dots are common points among different runs of data collection.



(a) Before Image Stitching (16 Runs)



(b) After Image Stitching (16 Runs)

Figure 5. Runway Image Stitching in MHIS-Airport.

The entire runway is divided into 455 rows with 8 slabs in each row. In total there are 186 sample units for the runway. Since the DHDV system equipped with PaveVision3D technology can collect full coverage of the runway data, the PCI survey is conducted for all the sample units without any systematic or random sampling as recommended in the FAA AC 150/5320-1. The runway's PCI is calculated based on all the sample units' individual PCI values. For each sample unit, the deduct values are determined for each distress type and severity level. The PCI value is calculated by subtracting the maximum Condition Deduct Values (CDV) from 100. The PCI values for the entire runway and runway segments between taxiways are provided in Table 2. The PCI evaluation results indicate that the runway is in excellent condition. The differences of the PCI values of runway segments between taxiways are insignificant.

Table 2.
PCI Evaluation Results for Runway.

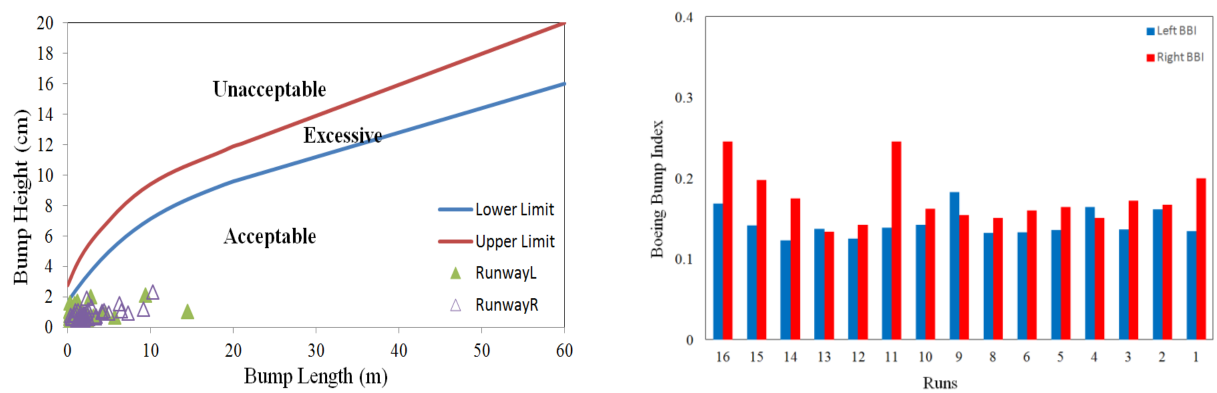
Location	Whole Runway	Runway Segment			
		Taxiway K-C	Taxiway C-E	Taxiway E-F	Taxiway F-A
PCI value	91.0	92.0	89.3	92.8	90.7

It should be acknowledged that the current MHIS-Airport software only has 2D capabilities. Many distress types, such as popouts and faulting (two primary surface issues as discussed in previous section), cannot be clearly identified based on 2D intensity images only. Since this is a newly-constructed runway and has not yet opened to traffic, there is no cracking observed on the runway surface. The primary distress identified during the PCI analysis for the runway is joint spalling. In addition, many surface issues, such as surface unevenness, groove problems, grinding related problems, are not defined in the PCI procedure, and therefore cannot be considered in the PCI analysis.

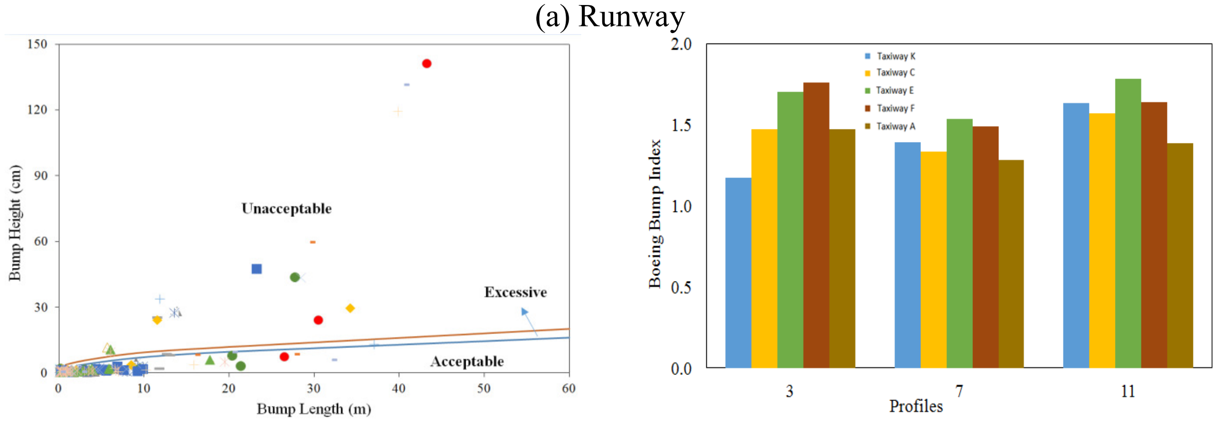
ROUGHNESS EVALUATION

Runway roughness affects the safe operation of an airplane, stress on aircraft component, and passenger comfort (FAA 2009). The Boeing Bump Index in the FAA AC 150/5380-9, *Guidelines and Procedures for Measuring Airfield Pavement Roughness*, was developed to quickly and simply identify roughness that can produce poor aircraft ride quality. This method evaluates the measured pavement profile and categorizes a single roughness event as "acceptable", "excessive" or "unacceptable" based on the event's amplitude and wavelength.

With longitudinal profiling data, airport runway bumps are identified. The height and length for each bump are plotted into the Boeing Bump evaluation chart, as shown in Figure 6. It can be seen that all the bumps on the runway locate within the “Acceptable” region, indicating that the runway roughness are acceptable for airplane operations. In Addition, Boeing Bump Index (BBI) has been fully implemented in the FAA ProFAA, a computer program for computing pavement profile roughness indexes. BBIs are calculated using ProFAA software for the longitudinal profiles at both wheelpaths for the 16 passes (with a total of 32 profiles), as shown in Figure 6.



(a) Runway



(b) Taxiways

Figure 6. Boeing Bump Evaluation.

The average of the BBI values for the runway is less than 0.3, which indicates that the bumps on the runway are in the "Acceptable" region.

Similar Boeing Bump based analyses are conducted for the five taxiways. Three longitudinal profiles (one on the north side, one in the center and one on the south side) are selected for each taxiway for Boeing Bump analysis. In total there are 24 critical bumps that fall into "Excessive" or "Unacceptable" region, in which 18 bumps (75%) are located within the runway/taxiway intersectional areas where runway crowns are constructed. The Boeing Bump evaluation charts for the five taxiways are also shown in Figure 6. BBI values are also calculated on taxiways using ProFAA in Figure 6. The average BBI is greater than 1.0 (approximately 1.5). Since the speed of airplanes on taxiway are usually much lower than that during landing or taking off on runway, the evaluation results for taxiway may not be as critical.

GROOVE EVALUATION

FAA Standard Groove Configuration

FAA has established standard groove configuration of 1/4-in. by 1/4-in. square grooves spaced at 1-1/2 in. center to center for rectangular grooves in FAA AC 150/5320-12C *Measurement, Construction, and Maintenance of Skid Resistant Airport Pavement Surfaces* (FAA, 1997) with allowable tolerance as illustrated in Table 3.

Table 3.
Groove Configuration and Its Tolerance (FAA, 1997).

Groove type	Standard Configuration (Unit: in)		Tolerance (Unit: in)		Acceptable range			
			Lower limit	Upper limit	Unit (inch)		Unit (mm)	
Rectangular	Depth	1/4	-1/16	1/16	0.19	0.31	4.76	7.94
	Width	1/4	0	1/16	0.25	0.31	6.35	7.94
	Spacing	1 1/2	-1/8	0	1.38	1.5	34.9	38.1

FAA AC 150/5320-12C also provides the minimum dimension requirements of groove depth and width for rectangular grooves (FAA, 1997):

- 90 percent or more of the grooves shall not be less than 3/16 in (4.76 mm);
- 60 percent or more of the grooves shall not be less than 1/4 in (6.35 mm);
- 10 percent or less of the grooves shall not be more than 5/16 in (7.94mm).

Groove Identification and Dimension Measurement

In order to identify grooves, mask filter is used to eliminate the general shape or trend of profiles and maintain the detailed information. The implementation of this algorithm consists of two steps: 1) averaging out the original profile with moving average filter; 2) subtracting the smoothed profile from the original profile. The selection of base length of moving average filter is critical for the identification of grooves. Moving windows with variant size are tested to determine the optimum base length so that the influence of grooves is minimized and the general profile shape retained. Subsequently geometry contour based algorithm is applied to the filtered profile to locate groove location. This algorithm is able to identify the minimum profile elevation or the deepest point within a potential groove. If the depth of the identified point exceeds a predefined threshold, it is considered as a groove.

Once the deepest point within a groove is determined, the starting and ending positions of the groove should be located. The filtered profile with moving average filtering is used as the reference line. A backward traversal technique is applied to determine the starting position of grooves. This algorithm starts from the deepest point of a groove, and traverses the pixel location backward to find smaller pixel value than that for the current pixel. It is assumed that the pixel value of the starting of each groove in the original profile is larger than the corresponding pixel value in the filtered profile. If such pixel is found, it is considered as the starting position of the groove. Similarly, forward traversal technique is used to find the ending position of a groove. Upon locating the two end points of a groove, groove dimension can be calculated in accordance with FAA Advisory Circular No. 150/5320-12C. An example profile with identified grooves is illustrated in Figure 7.

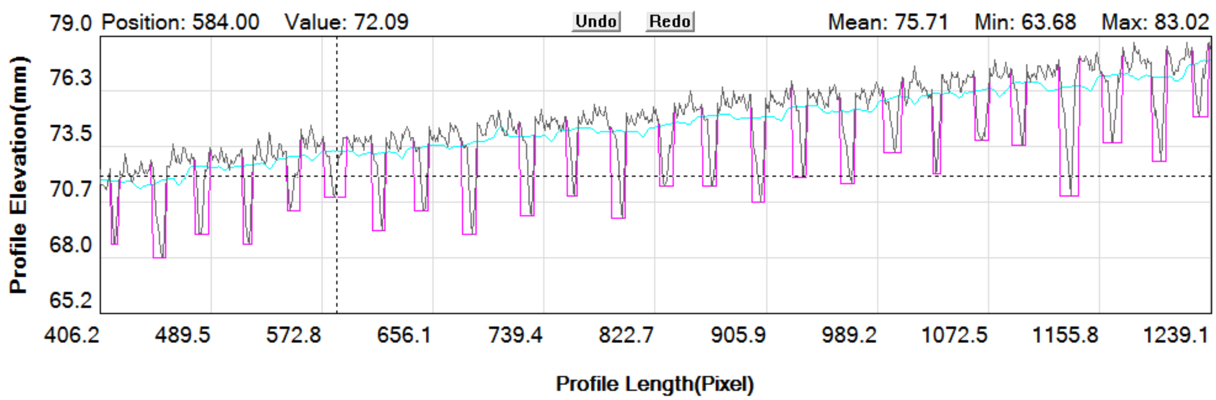


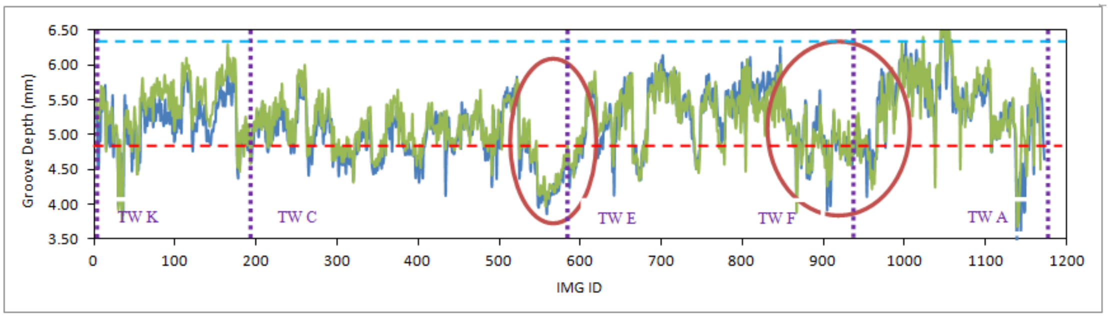
Figure 7. Groove Identification Results.

Groove Evaluation

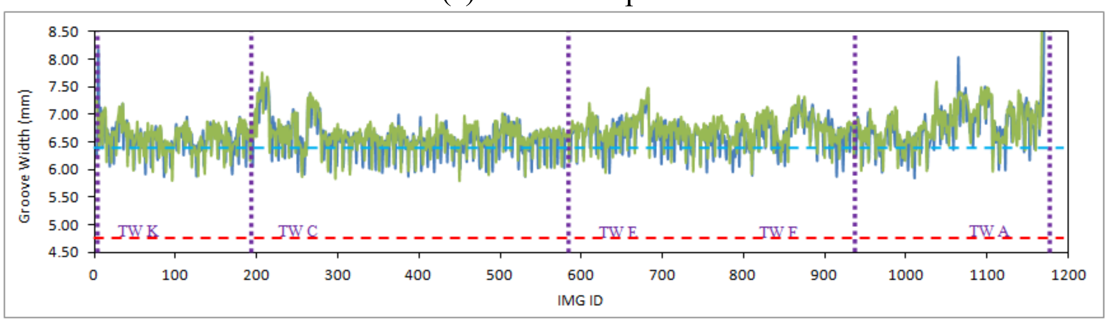
FAA recommends measuring runway surface profile along the centerline with a lateral offset (left and right) that approximates the aircrafts operating on airport runway (FAA, 2009). The width of the tested runway slab is approximately 18 ft. Therefore, slab #4 and slab #5 as shown in Figure 3 will be the primary runway keel surface during take-off and landing.

In this paper, groove results, including groove depth, width and spacing, for slab #4 are presented in Figure 8. The calculated groove dimensions based on the two PaveVision3D runs on this slab demonstrates very similar measurements. The standard dimension and the FAA required lower tolerance limit are shown in Figure 8 using dotted green and red lines. In terms of groove depth, the FAA lower tolerance groove depth is 3/16 in (4.76mm). Vast majority of the grooves (approximately 99.3%) have depths lower than the standard configuration defined in FAA AC 150/5320. There are many segments (about 18.8%) with groove depths less than the minimum tolerance of 3/16 inches. Particularly, groove depth around the intersections of runway with Taxiway E and Taxiway F are relatively shallower than other segments of the runway. For groove width and spacing, the mean values are close to the standard configuration values. Inconsistent groove width and spacing are also observed. The spacings of some grooves are much larger or smaller than the standard values. For other slabs, similar findings are observed as those for slab #4.

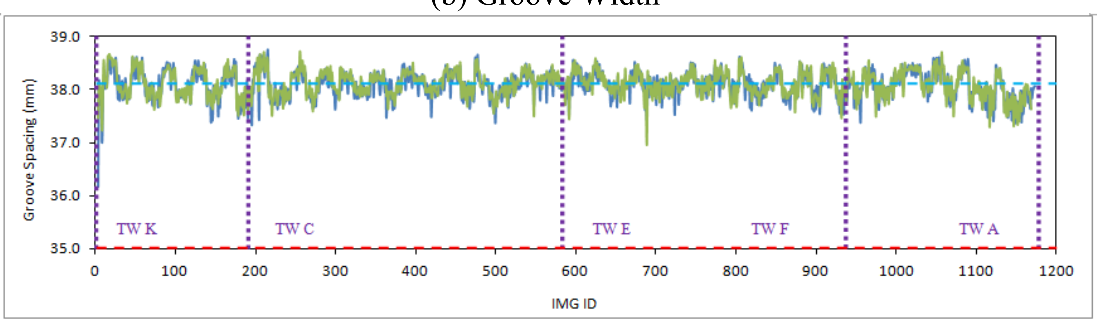
The groove evaluation results may seem to be illogical for a normally constructed runway. However, this new runway under evaluation has severe and apparent grooving problems to human eyes, among other construction problems. The uneven depths in adjacent grooves are very visible.



(a) Groove Depth



(b) Groove Width



(c) Groove Spacing

Figure 8. Groove Evaluation for Slab #4.

TRANSVERSE PROFILING AND CROSS SLOPE

SurPro 3500 is used to acquire the transverse profiling of the runway. Each transverse run starts from a runway edge light fixture located on the east side shoulder. For example, KC1 indicates that the profile is measured at the first edge light fixture in the runway segment between Taxiway K and Taxiway C. Several methods are utilized to calculate the cross slope, including AASHTO method, TxDOT method, and linear regression method. The mean values of the cross slope values from the three methods are calculated every foot. In total there are 47 transverse profiles. The distribution of the cross slope values is shown in Figure 9. Only 32.81% of the cross slope values fall within the designed range between 1.0% to 1.5%, 53.75% greater than 1.5% of slope, 12.41% within 0% and 1.0%, and 1.04% has negative cross slopes.

Figure 10 provides the average cross slope for each transverse profile on the runway for the west and east sides of the centerline. For the east half runway, the mean of the averaged cross slopes is 1.57% with the minimum 1.44% and maximum 1.75%. For the west half runway, the mean of the averaged cross slopes is 1.55% with the minimum 1.44% and maximum 1.68%. Comparing to the design values requiring 1.0% to 1.5% of cross slope, variations are observed. In some locations, the variations are significant.

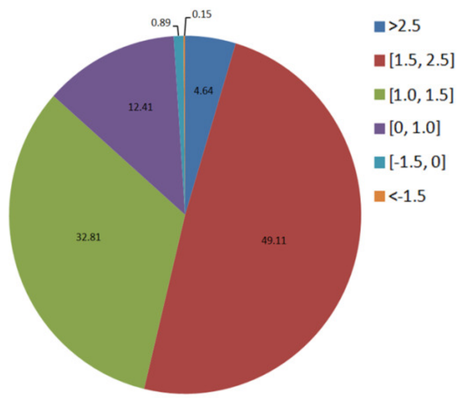


Figure 9. Distribution of Runway Transverse Cross Slope.

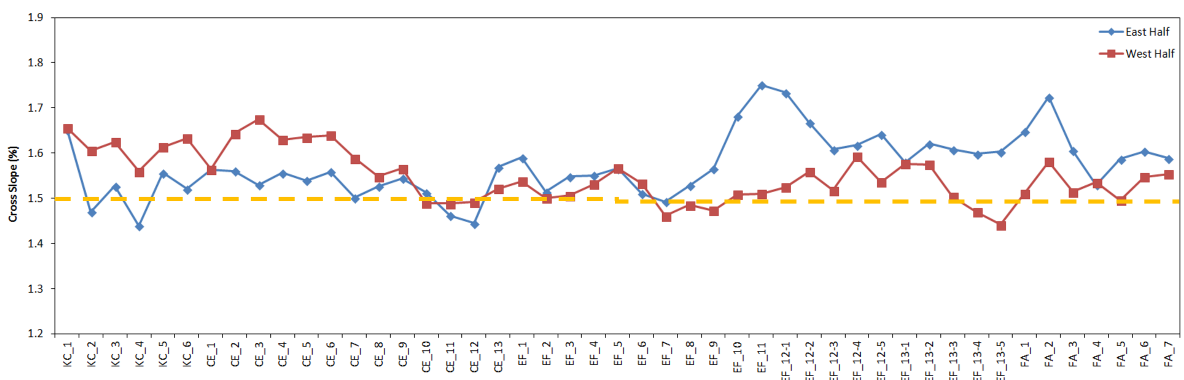


Figure 10. Runway Transverse Profiling and Cross Slope.

CONCLUSIONS

This paper presents the application of the newly developed 1mm 3D laser imaging technology to survey the runway and five taxiways. The PaveVision3D Ultra (3D Ultra) technology equipped with new generation accelerometers is capable of collecting pavement surface data at 1mm resolution at 60mph with the coverage of four meters. 16 passes of runway data collection in the longitudinal direction and 63 runs of taxiway data collection are conducted. The SurPro walking profiler is also used for the same runway survey as the reference. The collected surface data are used to approximate runway PCI analysis, longitudinal profiling and Boeing Bump analysis, groove evaluation, and transverse profiling. The new technology based on 1mm 3D laser imaging provides a high-performance surface evaluation device that is part of singular hardware platform for comprehensive NDT evaluation of airfield pavement surfaces.

Even though approximate PCI values for the runway are excellent due to lack of traditional distresses on the runway based on PCI definitions, substantial construction quality issues are identified with the 3D Ultra technology on the runway, such as slab unevenness, joint problems, pop outs, out-of-spec grooves, and other construction related quality problems.

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