A Vehicle-Based Laser System for High-Resolution DEM Development – Performance in Micro-topography Measurement

Peng Li[1], Naiqian Zhang[1], Larry E. Wagner[2], Fred Fox[2], Darrell Oard[1],
Hubert Lagae[3] and Mingqiang Han[1]

[1] *Department of Biological and Agriculture Engineering, Kansas State University, Manhattan, Kansas, USA*
[2] *USDA-Agricultural Research Service, Fort Collins, Colorado USA*
[3] *USDA-Agricultural Research Service, Manhattan, Kansas USA*
Corresponding Author: Naiqian.Zhang@ksu.edu

ABSTRACT

A vehicle-based laser measurement system was developed to measure the surface microtopography and to generate high-resolution digital elevation models (DEM). The accuracy of the system in microtopography measurement was evaluated in the laboratory by comparing the DEM data generated by this system with that generated by a more accurate, stationary laser profile meter for several surfaces, including an artificial sand-stone-ridged surface. DEM data was created by interpolating the 3D raw data into a regular, square grid using a two-dimensional, distance-weighted interpolation algorithm. The DEMs were compared using an image-matching method to calculate the correlation coefficient. A test to study the effect of ambient light on elevation measurement under indoor and outdoor environments was also conducted.

Correlation coefficients greater than 0.935 were achieved between the DEMs measured by the vehicle-based system and the stationary laser profile meter. The correlation coefficients among the four replications of the DEMs measured by the vehicle-based system were greater than 0.988, indicating that the vehicle-based laser system can provide consistent elevation measurements. Correlation coefficients among the DEMs of the sand-stone-ridged surface measured by the vehicle-based system at different times of the day and under different indoor fluorescent lighting conditions were all above 0.982. Correlation coefficients among DEMs taken at different times of the day and under different outdoor sunlight conditions were all above 0.971. These results indicated that neither the fluorescent light nor the sunlight had a significant effect on the measurements obtained by the vehicle-based laser system. The system provided consistent elevation measurements under both indoor and outdoor lighting conditions.

RÉSUMÉ

Un système laser de mesure sur véhicule a été élaboré pour mesurer la microtopographie de surface et générer des modèles numériques d’élévation [Digital Elevation Model (DEM)]) à haute résolution. La précision du système dans la mesure de la microtopographie a été évaluée en laboratoire en comparant les données DEM générées par ce système avec celles générées par un profilomètre laser stationnaire plus précis pour évaluer plusieurs surfaces, y compris une surface artificielle striée de pierres et de sable. Les données DEM ont été créées en interpolant les données brutes 3D dans une grille carrée régulière à l’aide d’un algorithme d’interpolation bidimensionnel pondéré par la distance. La comparaison des DEM a été effectuée à l’aide d’une méthode de comparaison d’images pour calculer le coefficient de corrélation. Un test visant à étudier l’effet de la lumière ambiante sur la mesure de l’élévation dans des environnements intérieurs et extérieurs a également été réalisé.

Des coefficients de corrélation supérieurs à 0,935 ont été obtenus entre les DEM mesurés par le système sur véhicule et le profilomètre laser stationnaire. Les coefficients de corrélation entre les quatre répétitions des DEM mesurés par le système sur véhicule étaient supérieurs à 0,988, ce qui indique que ce système peut fournir des mesures d’élévation consistantes. Les coefficients de corrélation entre les DEM de la surface striée de pierres et de sable mesurés par le système sur véhicule à différents moments de la journée et dans différentes conditions d’éclairage fluorescent intérieur étaient tous supérieurs à 0,982. Les coefficients de corrélation entre les DEM obtenus à différents moments de la journée et dans différentes conditions d’ensoleillement extérieur étaient tous supérieurs à 0,971. Ces résultats indiquent que ni la lumière fluorescente ni celle du soleil n’ont eu un effet significatif sur les mesures obtenues par le système laser sur véhicule. Ce système a fourni des mesures d’élévation consistantes dans des conditions d’éclairage intérieur et extérieur.

KEYWORDS

DEM, Interpolation, Image Matching, 3D, Laser Line Scanner

MOTS CLÉS

DEM, interpolation, mise en correspondance d’images, 3D, dispositif de balayage à ligne laser.

CITATION

Li, P., N. Zhang, L.E. Wagner, F. Fox, D. Oard, H. Lagae and M. Han. 2021. **A Vehicle-Based Laser System for High-Resolution DEM Development – Performance in Micro-topography Measurement.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada 63: 2.33-2.40. https://doi.org/10.7451/CBE.2021.63.2.33

INTRODUCTION

Studying soil surface microtopography is important to understanding the physical processes of soil erosion by wind and water. Thus, research on the methods of collecting microtopography data has received significant attention over the years, resulting in the development of various measurement systems based on different techniques. The techniques for measuring soil microtopography include pin meter (Podmore and Huggins, 1981; Radke et al., 1981; Wagner and Yu, 1991), chain method (Saleh, 1993; Merrill et al., 2001), infrared (Romkens and Wang, 1986), ultrasonic (Robichaud and Molnau, 1990), photogrammetry (Welch et al., 1984; Warner, 1995; Taconet and Ciarletti, 2007; Cierniewski et al., 2015; Gilliot et al., 2017), and laser (Bertuzzi et al., 1990; Huang and Bradford, 1990; Flanagan et al., 1995; Wilson et al., 2001; Darboux and Huang, 2003; Lichti and Jamtsho, 2006; Mizaei et al., 2012; Bretar et al., 2013; Thomsen et al., 2015). Most of the newer techniques used digital computers to store the measured microtopography data using digital elevation models (DEM), which significantly improved the throughput of data collection and resolution of the resulting DEM data.

A vehicle-based laser measurement system to measure surface microtopography was developed in the Instrumentation and Control Laboratory of Kansas State University. This system integrated a laser line scanner, a gyroscope sensor, and an RTK GPS with a data acquisition and control unit. A flexible mounting frame-rail mechanism was constructed to allow adjustment of scan area and height. For ease of transportation portability, the device frame was fitted in the bed of a small utility vehicle (Fig. 1). The design and component tests of the vehicle-based laser system are reported by Li et al. (2021). This paper reports the algorithms used in DEM development. It evaluates the accuracy of the system by comparing the DEM data derived by this system with that acquired by a reference stationary laser profile meter. The effect of ambient light on elevation measurement in indoor and outdoor environments is also studied.

Fig. 1. Vehicle-based laser system for surface micro topography measurement.

MATERIALS AND METHODS

Test surfaces

Several artificial surfaces were constructed to test the performance of the vehicle-based laser system in repeated microtopography measurement using both the vehicle-based laser system and the stationary laser profile meter under indoor and outdoor conditions. They were fixed in place with a spray adhesive so that the microtopography would not change in time: (1) a rectangular box placed on white paper, (2) four objects of known geometric shapes placed on a flat surface, and (3) a 1m x 1m artificial surface made up of sand, stones and ridges and enclosed in a wooden frame (Fig. 2). This surface included a sand zone with four ridges labelled a, b, c, and d; a stone zone; and a small 1.0 cm height wooden block (4.5 cm length, 5.5 cm depth). In this paper, only test results on the sand-stone-ridged surface are reported because this surface most closely resembled natural surfaces and was most complex in shape.

Reference DEM measurement

A stationary laser profile meter was used to produce reference DEM measurements for comparison with the vehicle-based laser system (Fig. 3). This stationary laser profile meter included three components: a laser distance sensor, NR-40-105 (Nova Range Inc., 2001), to measure surface elevation, a computer-controlled, motor-driven, two-dimensional traversing frame, and a data acquisition card, PC-CARD-DAS16/16AO (Measurement Computing Corp., 2007), plugged into a field laptop to control the motion of the laser-carriage and to register the elevation data. A LabVIEW program controlled the motion of the laser carriage on the two-dimensional traversing frame. Once the desired grid spacing was determined, scanning was performed automatically under the control of the computer.

The laser distance sensor was a CLASS IIIa product, which emitted a red beam of 670 nm wavelength, received a reflected beam, and calculated the distance based on the triangulation principle. It provided a 0.05 cm distance measurement accuracy within the 60 cm measurement range. This accuracy was higher than the vehicle-based laser measurement system can provide (Li, et al 2021). Thus, the DEM data produced by this profile meter was used as the reference for comparison.

Test Procedure

Both the vehicle-based laser measurement system and the stationary laser profile meter measured the sand-stone-ridged surface (Figs. 3 and 4). The vehicle-based laser measurement system scanned the 1m-by-1m surface at a sampling rate of 40 kHz, a mirror rotation speed of 1400 RPM, and a maximum range setting of 183 cm. The resulting spatial resolutions of the raw data in the

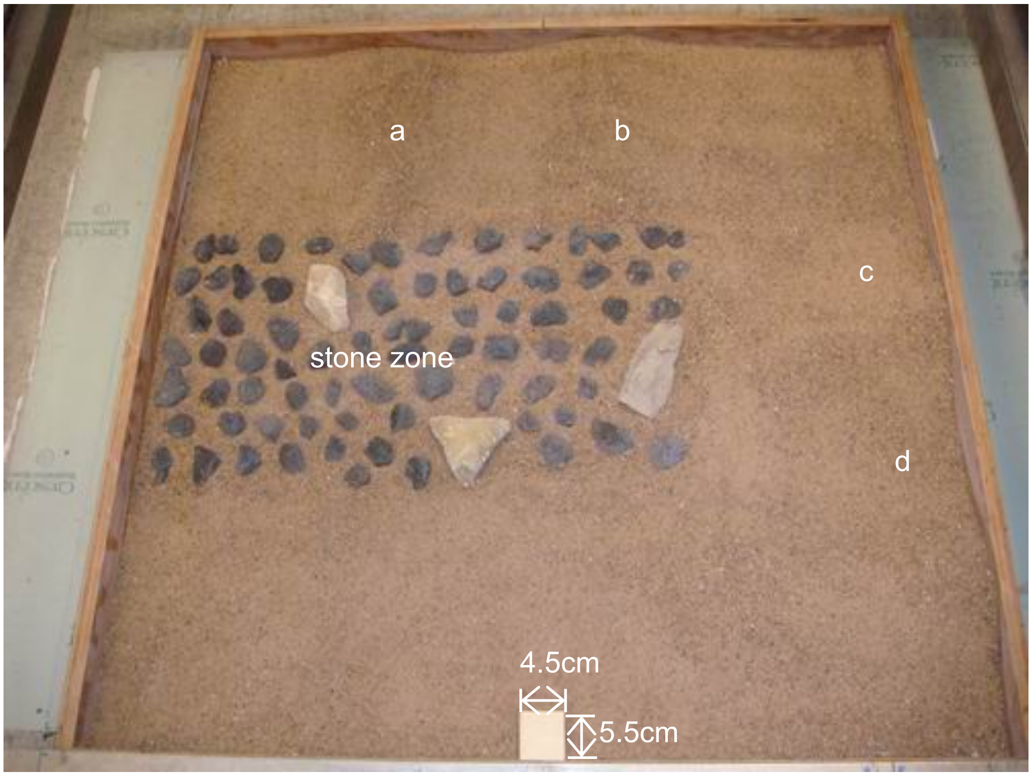

Fig. 2. An artificial test surface (1 m x 1 m). Locations a, b, c, and d are sand-ridged zones. The 1cm height block is located at the bottom center of the test surface.

longitudinal and lateral directions were both 0.3 cm. The scanner's carriage moved on the rail at a speed of 6 cm/s. For the stationary laser profile meter, the spatial resolutions of the measured data were 0.2 cm by 0.3 cm. The distance data generated by both systems were post-processed to generate the DEM data.

If the laser scanner is placed further away from the artificial surface or the measured area exceeds 1m by 1m, the measurement resolution in the lateral direction would be reduced. On the other hand, the speed of the carriage along the linear rail was the main factor that affected the measurement resolution in the longitudinal direction. The

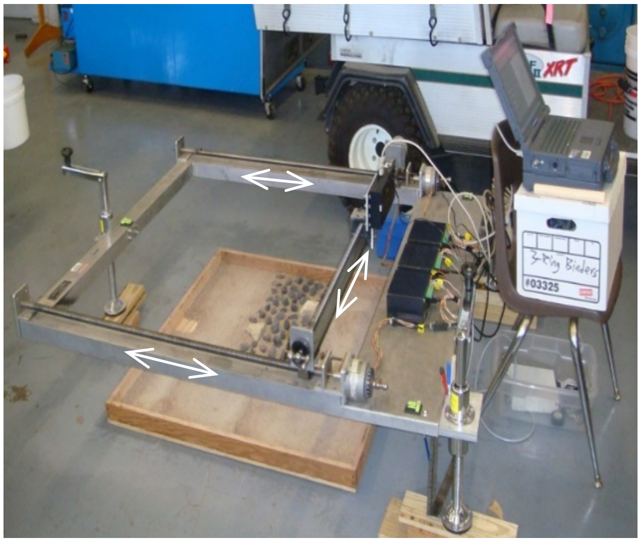

Fig. 3. Stationary laser profile meter used for obtaining reference DEMs.

Fig. 4. The vehicle-based laser system measures the DEM of the test surface.

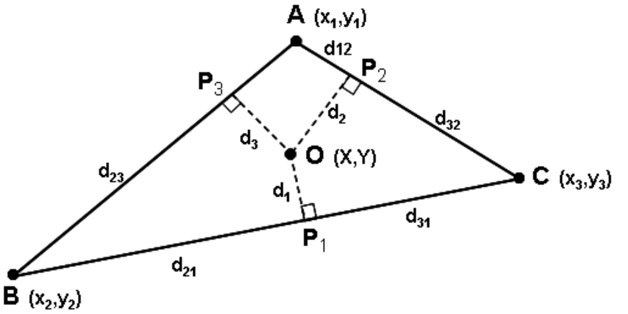

Fig. 5. Distance-weighted, three-nearest Neighbor Interpolation.

faster movement would reduce the resolution. Another limitation is the range of elevation measurement. The closest distance between the object and the laser scanner tested in the laboratory was 20 cm. Thus, the highest point of the artificial surface from the base plane should not exceed 163 cm. These are the limitations of the vehicle-based system on micro-topography measurement

Data post-processing

The first step of data post-processing was to convert the distance data to elevation data, which used the bottom surface of the sand-stone-ridged surface frame as the zero elevation plane. For the data generated by the stationary laser profile meter, this was done by simply subtracting the measured distance from the elevation of the lens of the laser sensor. For the vehicle-based laser measurement system, the height of the laser scanner carrier and the rotational angle of the rotating mirror in the laser scanner were used to calculate the elevation of each point. Because sampling was controlled by time in both systems, the sampling points did not fall on a regular grid. For comparison purposes, we needed to convert both data sets to a uniform square grid with grid spacings of 0.5 cm in both directions through interpolation.

A two-dimensional, three-nearest neighbour, distance-weighted interpolation algorithm (Zhang et al., 1989) was applied to the raw laser data generated by the stationary laser profile meter and the vehicle-based laser measurement system to generate the DEM data at the desired uniform grid spacing. For each cell on the regular grid, three data points on the raw laser data that had the shortest distances to the cell center, A(x_1, y_1), B(x_2, y_2), C(x_3, y_3), were used to determine the polynomial weighting functions (Fig. 5):

$$W_1(x_1,y_1) = d_1^2(d_2^2 d_{23}^2 + d_3^2 d_{32}^2) \quad (1)$$

$$W_2(x_2,y_2) = d_2^2(d_1^2 d_{13}^2 + d_3^2 d_{31}^2) \quad (2)$$

$$W_3(x_3,y_3) = d_3^2(d_1^2 d_{12}^2 + d_2^2 d_{21}^2) \quad (3)$$

where d_1, d_2, and d_3 were the distances between the center of cell O(x,y) and the three raw data points.

The elevation Z of cell O was then determined as the weighted average of the elevations of the raw points A, B, and C:

$$Z = \frac{W_1(x_1,y_1)z_1(x_1,y_1) + W_2(x_2,y_2)z_2(x_2,y_2) + W_3(x_3,y_3)z_3(x_3,y_3)}{W_1(x_1,y_1) + W_2(x_2,y_2) + W_3(x_3,y_3)} \quad (4)$$

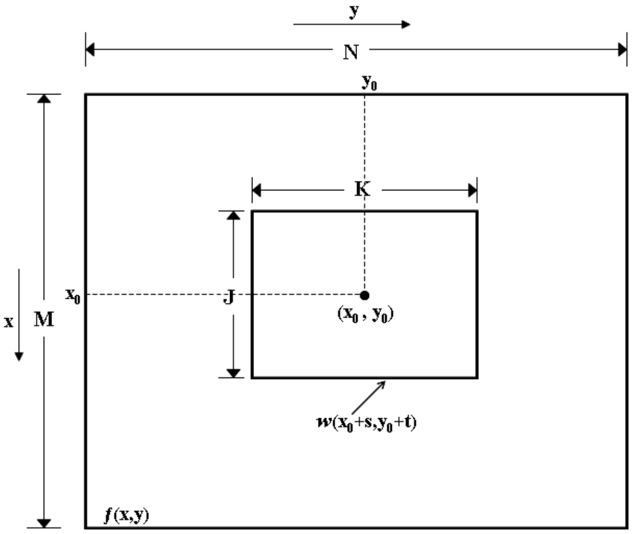

Fig. 6. Correlation function between the two measured DEM data (from Gonzalez and Woods, 2002).

where, z_1 to z_3 = the elevations at the three raw data points. After interpolation, the DEM data measured by the vehicle-based laser system and the stationary laser profile meter were compared on the same uniform grid spacing using the image matching method (Gonzalez and Woods, 2002), which calculated the correlation coefficient between the two DEM data sets. If the DEM data obtained by the stationary laser profile meter and the vehicle-based laser system were defined as *f*(x, y) of size M*N and *w*(x, y) of size J*K, respectively, the correlation function between *f* and *w* can be calculated as:

$$c(x,y) = \sum_{s=0}^{J-1}\sum_{t=0}^{K-1} f(s,t)w(x+s,y+t) \quad (5)$$

where, x = 0, 1, 2 …M-1, y = 0, 1, 2…N-1, and the summation is taken over the data region where w and *f* overlap.

Fig. 6 illustrates the procedure for computing *c*(x, y). As x and y varied, w moved within the area of *f*, giving the function *c*(x, y) at each location. The maximum value of *c* indicated the position where w best-matched *f*.

The correlation function given in Equation (5) had the disadvantage of being sensitive to changes in the amplitudes of *f* and w. A frequently used approach to overcome this difficulty is to use the correlation coefficient, which is defined as:

$$r(x,y) = \frac{\sum_{s=0}^{J-1}\sum_{t=0}^{K-1}\left[f(s,t)-\bar{f}(s,t)\right]\left[w(x+s,y+t)-\bar{w}\right]}{\left\{\sum_{s=0}^{J-1}\sum_{t=0}^{K-1}\left[f(s,t)-\bar{f}(\mathrm{s},t)\right]^2 \sum_{s=0}^{J-1}\sum_{t=0}^{K-1}\left[w(x+\mathrm{s},y+t)-\bar{w}\right]^2\right\}^{1/2}} \quad (6)$$

where, x = 0, 1, 2…, M-1, y = 0, 1, 2…, N-1, $\bar{w}$ is the average value of the elevations in w (computed only once), $\bar{f}$ is the average value of *f* in the region coincident with the

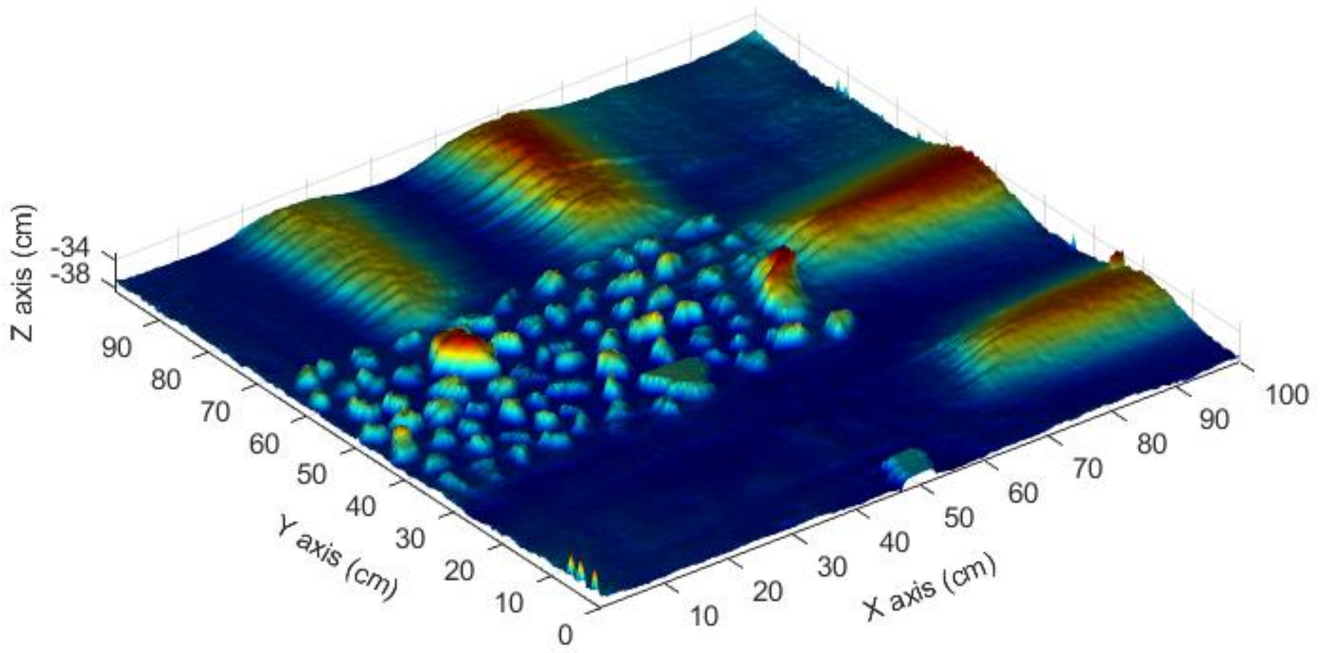

Fig. 7. DEM of sand-stone-ridged surface measured by the stationary laser profile meter.

current location of w, and the summations are taken over the coordinates common to both *f* and w.

Effect of Ambient Light

A test was conducted to study the effect of ambient light on elevation measurement under both indoor and outdoor environments. For this experiment, DEM data from the vehicle-based laser system derived at different lighting conditions were compared by calculating the correlation coefficients among the measured DEM data.

Fluorescent lamps (Philips cool white F32T8/TL841 /ALTO) were used as the illuminating source for the indoor test. The vehicle-based laser system measured the sand-stone-ridged surface at four different times in a day: 9:30 AM, 1:30 PM, 8:30 PM, and 11:30 PM. At each time, measurements were taken with and without the fluorescent light. For all measurements, the laser line scanner was configured at a sample rate of 40 kHz, a mirror rotation speed of 1400 RPM, and a maximum range setting of 183 cm. The laser carriage moved at a speed of 6.31 cm/s. At this speed, each scan was completed within 17 seconds.

The sand-stone-ridged surface was placed outdoors to investigate the effect of sunlight on the measurement and measured by the vehicle-based laser system at four different times - 10:30 AM, 1:30 PM, 3:30 PM, and 6:00 PM - on a sunny day. Two replications were taken at each time. The same scanner, mirror, and laser carriage settings were used for these tests.

RESULTS AND DISCUSSION

Accuracy of Elevation Measurements

DEMs of the sand-stone-ridged surface measured by the stationary laser profile meter and the vehicle-based laser system are displayed in Figs. 7 and 8, respectively. The four ridges in the sand area, the stone zone, and the small wooden block can be easily observed on both DEMs. To quantitatively evaluate the accuracy of the laser system, correlation coefficients between the reference and four replications of the measured DEMs were calculated. To improve the measurement accuracy, two spatial filters, the median threshold filter and the median filter, were also applied to the raw laser data before and after the interpolation. Correlation coefficients among the reference DEM and DEMs obtained by the vehicle-based laser system are listed in Table 1.

The correlation coefficients between the DEMs measured by the stationary laser profile meter and the vehicle-based laser system were greater than 0.935. The correlation coefficients among the four replications of the DEMs measured by the vehicle-based system were greater than 0.988. These results indicated that the vehicle-based laser system generated the DEM for a sand-stone-ridged surface with satisfactory accuracy and good repeatability.

Ambient light effect

Table 2 lists the correlation coefficients among the DEMs of the sand-stone-ridged surface measured by the vehicle-

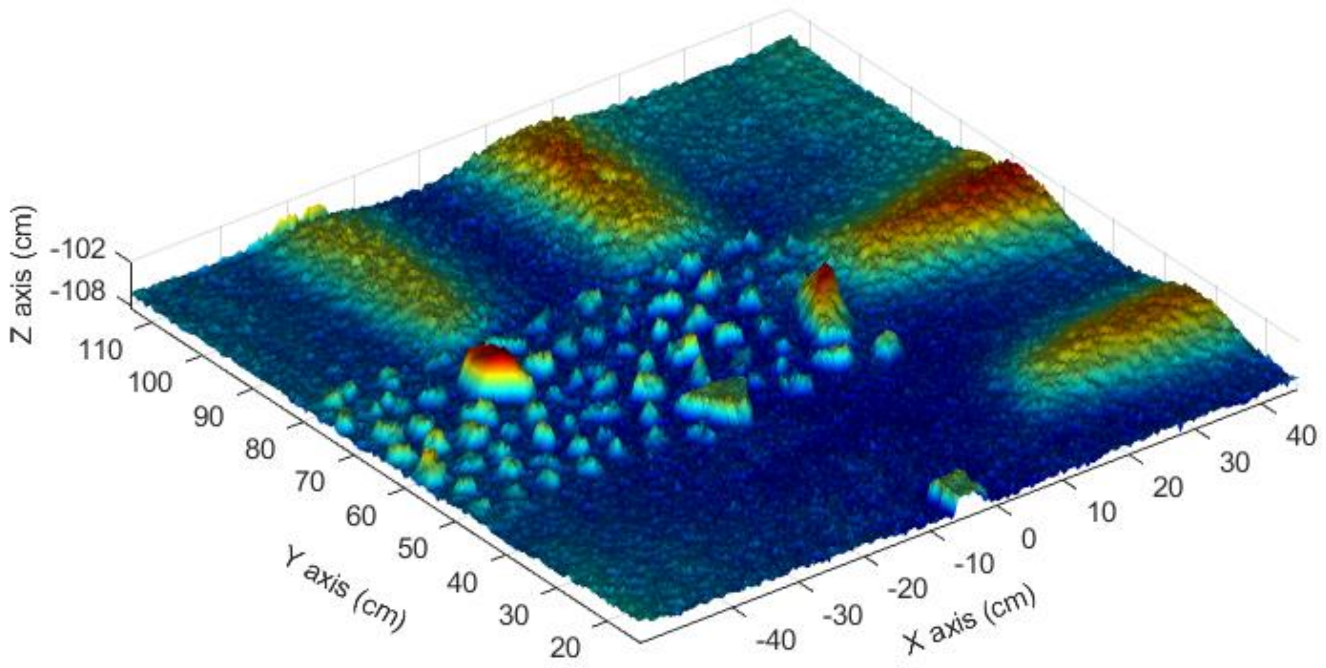

Fig. 8. DEM of sand-stone-ridged surface measured by the vehicle-based laser system.

based system under different indoor lighting conditions at different times of the day. Table 3 summarizes the correlation coefficients of the DEMs taken at different times of the day in an outdoor environment. All the correlation coefficients were greater than 0.982 and 0.971 for indoor and outdoor conditions, respectively, indicating that neither fluorescent light nor sunlight had a significant effect on the measurements obtained by the vehicle-based laser system. The vehicle-based laser system provided consistent elevation measurements under indoor and outdoor lighting conditions.

Table 1. Correlation coefficients among the DEMs obtained by the stationary laser profile meter and vehicle-based laser system for the sand-stone-ridged surface.

		Stationary laser profile meter	Vehicle-based laser system			
			Rep 1	Rep 2	Rep 3	Rep 4
Stationary meter profile meter		1	0.9540	0.9393	0.9359	0.9459
Vehicle-based laser system	Rep 1	0.9540	1	0.9891	0.9884	0.9885
	Rep 2	0.9393	0.9891	1	0.9917	0.9886
	Rep 3	0.9359	0.9884	0.9917	1	0.9916
	Rep 4	0.9459	0.9885	0.9886	0.9916	1

Table 2. Correlation coefficients among DEMs were measured by the vehicle-based system under different indoor lighting conditions at different times during the day.

		9:30 AM		1:30 PM		8:30 PM		11:30 PM	
		Light on	Light off	Light on	Light off	Light on	Light off	Light On	Light off
9:30 AM	Light on	1	0.9898	0.9880	0.9902	0.9886	0.9913	0.9877	0.9898
	Light off	0.9898	1	0.9903	0.9892	0.9888	0.9929	0.9910	0.9931
1:30 PM	Light on	0.9880	0.9903	1	0.9862	0.9825	0,9885	0.9927	0.9905
	Light off	0.9902	0.9892	0.9862	1	0.9874	0.9915	0.9885	0.9898
8:30 PM	Light on	0.9886	0.9888	0.9825	0.9874	1	0.9911	0.9890	0.9910
	Light off	0.9913	0.9929	0.9885	0.9915	0.9911	1	0.9892	0.9931
11:30 PM	Light on	0.9877	0.9910	0.9927	0.9885	0.9890	0.9892	1	0.9907
	Light off	0.9898	0.9931	0.9905	0.9898	0.9910	0.9931	0.9907	1

Table 3. Correlation coefficients among DEMs measured by the vehicle-based system at different times of the day under sunlight.

		10:30 AM		1:30 PM		3:30 PM		6:00 PM	
		Rep 1	Rep 2	Rep 1	Rep 2	Rep 1	Rep 2	Rep 1	Rep 2
10:30 AM	Rep 1	1	0.9790	0.9843	0.9791	0.9724	0.9739	0.9748	0.9746
	Rep 2	0.9790	1	0.9726	0.9778	0.9763	0.9732	0.9767	0.9766
1:30 PM	Rep 1	0.9843	0.9726	1	0.9718	0.9780	0.9872	0.9785	0.9876
	Rep 2	0.9791	0.9778	0.9718	1	0.9751	0.9883	0.9798	0.9829
3:30 PM	Rep 1	0.9724	0.9763	0.9780	0.9751	1	0.9810	0.9942	0.9854
	Rep 2	0.9739	0.9732	0.9872	0.9883	0.9810	1	0.9768	0.9920
6:00 PM	Rep 1	0.9748	0.9767	0.9785	0.9798	0.9942	0.9768	1	0.9823
	Rep 2	0.9746	0.9766	0.9876	0.9829	0.9854	0.9920	0.9823	1

CONCLUSIONS

The accuracy of the vehicle-based laser system in elevation measurement was evaluated by comparing the DEM models generated by the vehicle-based laser system for a sand-stone-ridged surface with that generated by a more accurate, stationary laser profile meter for the same surface. The correlation coefficient between the DEMs was calculated. For the four replications, the lowest correlation coefficient between the DEMs measured by the two systems was 0.935, indicating good accuracy for the vehicle-based system in DEM measurement. The lowest correlation coefficient between the DEMs generated by the vehicle-based system in four replications was 0.988, indicating good repeatability in DEM measurement.

Results of the ambient light test indicated that neither sunlight nor fluorescent light has a significant effect on the elevation measurement of the vehicle-based laser system. The system can provide consistent elevation measurements under various indoor and outdoor lighting conditions.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support of the U.S. Department of Agriculture, Agricultural Research Service (Agreement No.58-5430-8-317).

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