2017

Stored Grain Volume Measurement Using a Low Density Point Cloud

Aaron P. Turner
University of Kentucky, aaron.turner@uky.edu

Joshua J. Jackson
University of Kentucky, joshjackson@uky.edu

Nicole K. Koeninger
University of Kentucky, nicole.koeninger@gmail.com

Samuel G. McNeill
University of Kentucky, sam.mcneill@uky.edu

Michael D. Montross
University of Kentucky, michael.montross@uky.edu

See next page for additional authors

Authors
Aaron P. Turner, Joshua J. Jackson, Nicole K. Koeninger, Samuel G. McNeill, Michael D. Montross, Mark E. Casada, Josephine M. Boac, Rumela Bhadra, Ronaldo G. Maghirang, and Sidney A. Thompson

Stored Grain Volume Measurement Using a Low Density Point Cloud

Notes/Citation Information
Published in *Applied Engineering in Agriculture*, v. 33, issue 1, p. 105-112.

Digital Object Identifier (DOI)
https://doi.org/10.13031/aea.11870

TECHNICAL NOTE:

STORED GRAIN VOLUME MEASUREMENT USING A LOW DENSITY POINT CLOUD

A. P. Turner, J. J. Jackson, N. K. Koeninger, S. G. McNeill, M. D. Montross, M. E. Casada, J. M. Boac, R. Bhadra, R. G. Maghirang, S. A. Thompson

ABSTRACT. *This technical note presents the development of a new apparatus and data processing method to accurately estimate the volume of stored grain in a bin. Specifically, it was developed to account for the variability in surface topography that can occur in large diameter bins when partially unloaded. This was accomplished using a laser distance meter to create a low density point cloud, from which a surface was interpolated using ArcMap geoprocessing tools. The manually controlled and portable system was designed to hold the laser distance meter and provided a common reference point. The data from the laser distance meter was transmitted to a tablet PC via Bluetooth. Measurement of an empty hopper bottom bin (4.6 m in diameter and 6.5 m tall) demonstrated that the system was able to measure a known volume within 0.02%, and repeated measures of an empty flat bottom bin (1.8 m in diameter, and 5.7 m tall) were within 0.29% of the known volume. Two applications are presented which highlight the system's ability to capture complex surfaces, as well as limitations that result from fill scenarios where the field of view was limited.*

Keywords. *Grain surface, Spatial modeling, Stored grain management.*

In order to inventory stored grain, the volume of grain in storage must be determined. The accurate assessment of grain within a bin typically requires an operator to determine both the bin geometry (cross-sectional area, eave height, and plenum height) and the headspace (distance between the eave and the grain surface). The headspace measurement is often made using a weighted fiberglass tape measure with corrections made for the grain surface topography. Correction factors applied for the grain surface are adequate and straight forward when the surface is level (no correction needed) or when a uniform, centered surcharge or discharge cone is present. However, estimating complex surface topologies of uneven grain make the implementation of accurate correction factors more arduous. Turner et al. (2016a) found significantly different volume estimates when bins with uneven surface topography were measured before and after leveling.

Evolution in bin construction has led to a growth in bin capacity and unloading options. This is pertinent for two reasons. First, the grain surface represents a larger portion of the total volume as the bin height to diameter ratio decreases (Turner et al., 2016a), and second, alternative unloading methods, such as side draws, result in a surface topography that is difficult to estimate. The purpose of this study was to develop a portable bin measurement system and supporting data processing methods to better estimate the volume of stored grain under these irregular conditions.

MATERIALS AND METHODS

MEASUREMENT SYSTEM DEVELOPMENT

To account for the difficulties that arise in measuring irregularly shaped surfaces, an alternative measuring system

Submitted for review in April 2016 as manuscript number PRS 11870; approved for publication as a Technical Note by the Processing Systems Community of ASABE in October 2016.

Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA. The USDA is an equal opportunity provider and employer.

The authors are **Aaron P. Turner, ASABE Member,** Engineer Associate, **Joshua J. Jackson, ASABE Member,** Graduate Research Assistant, **Nicole K. Koeninger, ASABE Member,** Graduate Research Assistant, **Samuel G. McNeill, ASABE Member,** Associate Extension Professor, and **Michael D. Montross, ASABE Member,** Professor, Department of Biosystems and Agricultural Engineering, University of Kentucky, Lexington, Kentucky; **Mark E. Casada, ASABE Member,** Research Agricultural Engineer, USDA-ARS Center Grain and Animal Health Research (CGAHR), Stored Product Insect and Engineering Research Unit (SPIERU), Manhattan, Kansas; **Josephine M. Boac, ASABE Member,** Research Associate, **Rumela Bhadra, ASABE Member,** Research Associate, and **Ronaldo G. Maghirang, ASABE Member,** Professor, Department of Biological and Agricultural Engineering, Kansas State University, Manhattan, Kansas; **Sidney A. Thompson, ASABE Member,** Professor, College of Engineering, University of Georgia, Athens, Georgia. **Corresponding author:** Michael D. Montross, Biosystems and Agricultural Engineering, University of Kentucky, Lexington, KY 40546-0276; phone: 859-218-4319; e-mail: michael.montross@uky.edu.

was developed to map the grain surface using a low density point cloud. The system utilizes a laser distance meter (Leica Disto D8, Leica Geosystems, Norcross, Ga.), a modified miter gauge, and an aluminum guide block. According to manufacturer specifications, the Leica D8 laser meter has a measuring range of 200 m and a stated accuracy of ±1.0 mm up to distances of 30 m with a deterioration in measuring accuracy of ±0.1 mm/m for distances over 30 m. The accuracy of the tilt sensor was stated to be between -0.1 to 0.2°. The laser was mounted on a V120 Incra miter gauge (Incra Precision Tools, Dallas, Tex.) which allows the laser to rotate at precise angles. The miter gauge can rotate 60° to either side of zero at 1° intervals. The system is clamped to the manhole at the top of the bin using two adjustable clamps to create a rigid measuring platform (fig. 1a). With a slight modification, the system also works for concrete silos (fig. 1b). Figure 1c and 1d demonstrate how the measurement system is mounted on two grain bins. The system was designed such that the axis rotated about a common origin from which the distance meter was referenced.

Once attached to the bin, the system was located in space by referencing the origin of the measurement device to the eave of the bin (the intersection of the wall and roof). Figure 1d shows the positioning of the laser meter to record the location of the eave and provided an origin for the measuring device. Figure 2 shows the native coordinate system used to capture all points. The orientation of the XY plane relative to the horizontal was set using a bullseye level. The grain surface was then swept along each azimuth (angle set with miter gauge) through a range of polar angles (angle determined by rotating the laser distance meter) from the interface of the grain and the wall to the opposite grain/wall interface. This was done for a range of azimuth angles over 120° in increments of 15°. A 2-D representation of these points is shown in figure 3. Points taken along each azimuth represent a straight line in the XY plane, and the number of points along each azimuth was controlled by the speed at which the distance meter was rotated, which was adjusted to ensure the surface was well represented. The azimuth angle was recorded manually, and the laser distance meter transmitted the polar angle and distance to a tablet via Bluetooth at a frequency of 1 sample/s.

(a) (b) (c) (d)

Figure 1. Bin measuring system being mounted on a typical steel bin (a), use on a concrete silo (b), and final mounting on two bins (c) and (d).

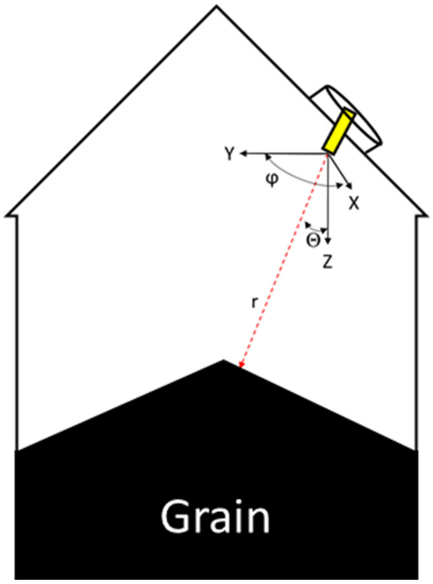


Figure 2. Representation of the native coordinate system of the bin measurement system. Θ is the polar angle, φ is the azimuth angle, and r is the distance from the origin to the grain surface.

DATA PROCESSING

Several processing steps were required to model the grain surface and determine the bin volume from the low density point cloud and bin metadata. Initial data processing and coordinate transformations were handled in MATLAB (MATLAB2014a, The MathWorks Inc. Natick, Mass.). An automated geoprocessing workflow was developed using ModelBuilder (ArcMap 10, ESRI, Redlands, Calif.) to create the bin surface, and the final grain surfaces were visualized in a 3-D format using ArcScene (ArcScene 10, ESRI, Redlands, Calif.).

During initial processing in MATLAB, the grain depth at each point was determined by mathematically transforming the angles and distances collected from the laser. The first step was to convert the collected point cloud data from spherical to Cartesian coordinates. The X and Y coordinates formed the horizontal plane, and were not adjusted because the measurement device was used as the XY origin. The next step was to determine the Z coordinate, which represented the final elevation of the grain surface relative to the bin floor. In order to calculate this value, the elevation from the grain surface to the reference plane (h), eave height (distance from the bin floor to the eave of the bin), and the measurement taken from the measurement device to the eave are needed. The final elevation was calculated using the following equation:

$$Z = H + sin(\Theta)*\mathrm{r} - \mathrm{h} \quad (1)$$

where

Z = final elevation of the grain surface relative to the bin floor, m (ft)
H = height from the bin floor to the eave, m (ft)
Θ = polar angle between origin and eave (°)
r = distance from the origin to the eave, m (ft)
h = original elevation from the measurement system to the grain surface (headspace), m (ft)

After transformation, the low density point cloud was visually inspected to remove any erroneous points that captured obstructions in the bin (structural supports, temperature cables, ladder, etc.).

The tabular data from the MATLAB processing was added to ArcMap in the Cartesian coordinate system (x, y, and z) and a feature class was created (exported) from this data. The data frame properties of the map and display units of the layer were defined in feet. The geoprocessing tools within ArcMap were linked together and processed with ModelBulder using the procedure shown in figure 4. Within the model, all of the measured points along the grain surface was established as the only input feature. Parameters defined within model were grain bin diameter and height of the bin floor (to account for the plenum). The first processing step was to create a circular bounding geometry that encompassed the data set in the XY plane. The center of the bounded circle feature was established with the mean center tool. A buffer that represented the bin diameter was created about the center point. An additional field within the attribute table was added for the bin floor height, and the 3-D attributes were created for the buffered polygon. For the measured surface points, the Kriging method was used to interpolate the surface of the grain (Erdogan, 2009; Oliver and Webster, 1990). The resulting raster was converted to a Triangular Irregular Network (TIN). TINs are commonly used in engineering applications to calculate areas and volumes (ESRI, 2012; Bhargava et al., 2013). The TINs allowed for the surface model to be displayed and stored in a 3-D format. Finally, the polygon volume tool allowed for the volume between the grain surface (a TIN feature) and bin floor (a polygon feature) to be calculated. The 3-D visualization of the bin floor and grain surface as a both a points and TIN feature was conducted with ArcScene. The actual grain surface and surface model generated from the point cloud data within a

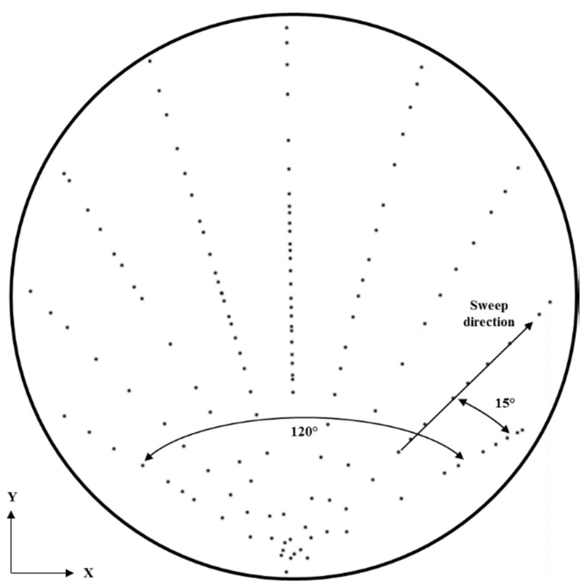


Figure 3. XY plane representation of the measurement distribution over the bins cross section with the total azimuth of 120° in 15° increments.

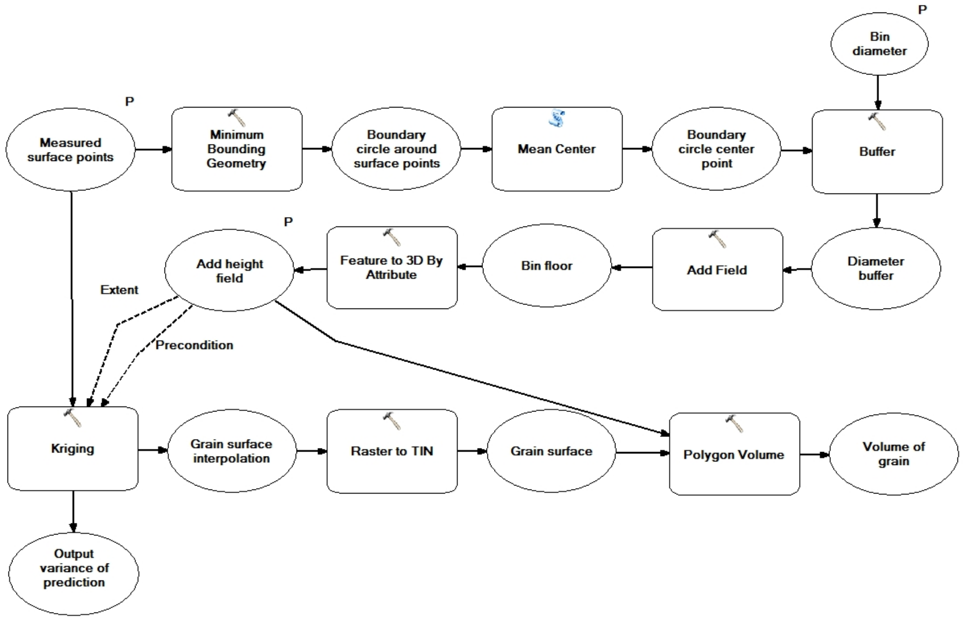


Figure 4. Flow chart of ModelBuilder procedure used to determine the volume.

bin 27.4 m in diameter is shown in figures 5a and 5b, respectively. The grain surface was formed by partially unloading the bin from two side draws.

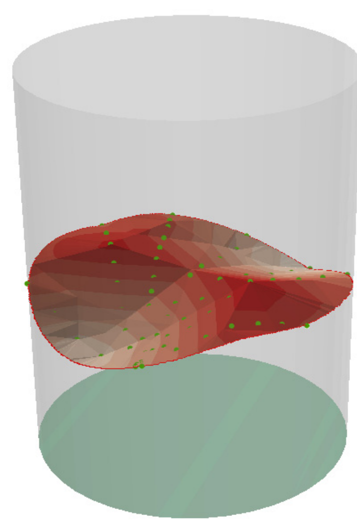
APPLICATION

The viability of the bin measurement system and modeling procedure was assessed by measuring two bins of known volume. The volume bounded by an empty hopper bottom bin was selected for measurement because the hopper provided a non-level (conical) shape for measurement. The bin was nominally 4.6 m in diameter, and the cylinder portion was 6.5 m from the top of the hopper to the eave with a hopper angle of 45°. For this scenario, the XY reference plane was located at the eave instead of at the bin floor, and the volume between the reference plane and the measured conical surface was estimated. A second flat bottom bin nominally 1.8 m in diameter and 5.7 m tall was measured in triplicate following a similar procedure.

Additionally, the repeatability of the bin measurement system was assessed by performing multiple measurements on four bins ranging from 8.2 to 11.0 m in diameter and from 6.1 to 9.4 m in height. The bins were in various states of fill, which allowed the system to be evaluated over a range of grain heights. Each bin was measured once by one operator with one device and two additional measurements were taken by two different operators using a second device.

The bin measurement system and modeling procedure was then tested at two different grain facilities. The first study was conducted at a commercial grain facility in Brown City, Michigan, in a corrugated steel grain bin 27.4 m in diameter and 24.4 m tall filled with soft red winter wheat. Measurements

(a)



(b)

Figure 5. (a) Grain surface topography due to two side draws in a 27.4 m diameter bin and (b) surface generated from the point cloud measurements of this bin.

were taken before and after 986.6 t (approximately 1,277.9 m^3 using the standard test weight) of wheat was removed from the bin. As discussed in the results, the view from the access door was initially obstructed, which was not suitable for the bin measurement system. To overcome this, the initial volume of grain was estimated by creating a solid model of the bin using Autodesk Inventor Pro (Autodesk Inc., San Rafael, Calif., 2015). The model was based on several point and angle of repose measurements taken with the laser distance meter by hand. The post unload measurements were made using the bin measurement system.

The difference in the before and after predicted inventory was compared to the actual mass of grain removed as determined from scale weights obtained from the cooperator. To convert the measured volume to an inventory estimate, the grade samples taken while unloading were evaluated to determine the pressure-density behavior as described by Turner et al. (2016b). This was done because the general compressibility equation for soft red winter wheat presented in Thompson and Ross (1983) was based on a limited number of samples, and the volume of grain removed between measurements was small relative to the total volume in storage. The main focus of this study was volume determination, thus it was advantageous to specifically tailor the compressibility equation to this bin. The predicted mass was then determined as described by Thompson et al. (1987) and McNeill et al. (2008).

The second case study took place at a farm scale operation in Midland, Michigan, where three corrugated steel grain bins were evaluated. Two of the bins were 14.6 m in diameter and 10.5 m tall; while the third bin was 4.6 m in diameter by 8.9 m tall with a 45° hopper. Each bin was filled with corn. Here, inventory was estimated using the WPACKING program (Thompson et al., 1987; 1991), which functions on the same procedure applied to the wheat bin in the first case study. However, in this case, the compressibility equation used in WPACKING was from Thompson et al. (1987) as validated by Bhadra et al. (2015). The actual mass of grain was determined from scale weights obtained from the cooperator after unloading.

Results and Discussion

Measurement of a Known Volume

An empty hopper bottom bin was measured to assess how well the system was able to estimate a known volume (fig. 6). The volume bounded by the bin was calculated to be 119.04 m^3. The volume estimated by the bin measurement system was determined to be 0.02% less than the actual volume and demonstrated that the measurement system produces an adequate representation of the surface.

In a flat bottom bin, the mean volume estimated was 15.02 m^3 with a standard deviation of 0.001 m^3, 0.29% less than the actual volume. This further demonstrated the sensitivity and capability of the system.

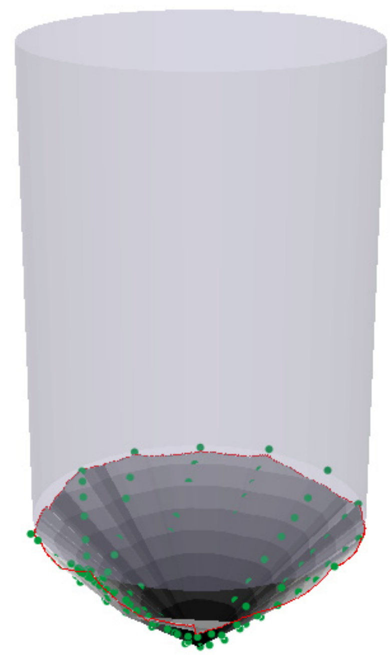


Figure 6. Point cloud and surface estimation of 4.6 m diameter bin with a 45° hopper.

Repeatability

Bins in varying states of fill were measured multiple times by multiple operators using two devices to examine the repeatability of the bin measurement system. Table 1 shows the results of these measurements. The mean volume measured ranged from 63.3 to 392.7 m^3, and the equivalent level height of grain ranged from 1.2 to 4.2 m. This allowed the variation in estimated volume to be examined over a range of grain volumes and headspace measurements (distances from the eave to equivalent level height of grain). The standard deviations in volume for three of the bins, including the bin with the largest head space, was $\leq$ 2.4 m^3, and the corresponding standard deviation in equivalent level height was $\leq$ 0.04 m. A single bin (no. 4), had a standard deviation in volume of 4.6 m^3 and 0.09 m in height, which was approximately double what was seen in the other bins.

Case Studies

Two case studies were evaluated to demonstrate the performance of the bin measuring system. The first case was a large commercial corrugated steel bin measured before and after 986.6 t (36,250 bu) of wheat were removed from the bin. Using the standard test weight of wheat, approximately 1,277.9 m^3 of grain was removed from the bin. Two main points can be drawn from this example. Initially, the bin was partially unloaded from a side draw opposite the access point (fig. 7a). Grain on the high side of the bin obstructed the view of the grain surface, making the bin measurement system unsuitable for this scenario. The profile shown in figure 7a was constructed using Autodesk Inventor Pro 2015 to estimate the initial volume based on several point and angle of repose measurements. The grain surface was primarily modeled using a cylinder and an inverted cone with a constant angle of repose that was centered at the side-draw unloading well. The initial volume estimate was 12,613.7 m^3.

Table 1. Descriptive statistics of mean grain volume, standard deviation of the volume (σ_v), and standard deviation in equivalent level height (σ_H) for bins with multiple measurements (n=3).

Bin	Diameter (m)	Eave Height (m)	Surface Condition	Equivalent Level Height (m)	Headspace (m)	Mean Volume (m^3)	σ_v (m^3)	σ_H (m)
1	11.0	9.4	Inverted, centered	4.2	5.2	392.7	2.4	0.03
2	8.2	6.1	Level, slight incline	3.5	2.6	185.3	1.9	0.04
3	8.2	7.4	Partial surcharge cone, off centered	1.2	6.2	63.3	2.2	0.04
4	8.2	7.4	Partial surcharge cone, off centered	1.6	5.8	87.5	4.6	0.09

Figure 7b shows the same bin after 986.6 t of wheat was unloaded from the bin via a center well. This illustrates an ideal application for the measurement system in that the resulting surface topography was clearly visible and was complex enough to warrant the use of the bin measurement system. The total volume estimated in figure 7b was 11,374.3 m^3.

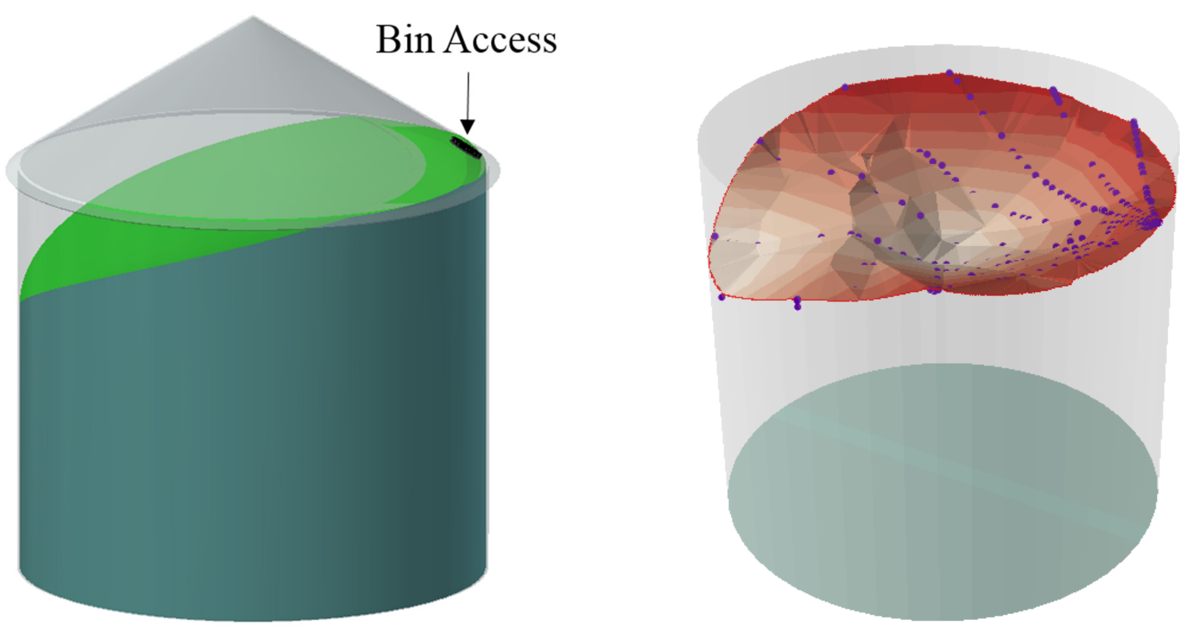
The average test weight and moisture content was 775 kg/m^3 (60.2 lb/bu) and 12.3% w.b., respectively. The inventory was estimated at 10,225.4 t (375,717 bu) before and 9,213.8 t (338,547 bu) after unloading (respective combined test weight and packing adjustments were 1.050 and 1.049). This resulted in an estimated change of 1011.6 t (37,169 bu), over predicting the actual mass of grain removed by 25.0 t (919 bu) or 2.55%. This error is the equivalent of 0.055 m (0.18 ft) in the equivalent level height of grain. This error was acceptable given it was based on the difference between two surface estimates (one of which was based on only few key points measured and recorded by hand), and the change measured was only approximately 10% of the total mass of grain in the bin.

The second case shows an example of how the system was applied to three different bins on a farm-scale operation. The estimated surfaces are shown in figure 8. Figure 8a shows a grain surface formed by unloading via a side-draw; while figure 8b shows a grain surface containing a partially inverted cone. Both of these bins were 14.6 m in diameter and 14.5 m tall, and the volume of grain was estimated to be 1,650.7 and 1,181.2 m^3, respectively. The third bin was 4.6 m in diameter and 8.9 m tall with a 45° hopper. The hopper bottom bin, figure 8c, illustrates a caveat with the current processing system. The grain surface consisted of an off-center partial cone. The estimated volume was 127.5 m^3, but this neglected the 12.5 m^3 of grain in the hopper, which had to be manually added.

The average test weight and moisture content was 741 kg/m^3 (57.53 lb/bu) and 14.7%w.b., respectively. This resulted in predicted masses of 1,274.8, 907.0, and 107.5 t (respective combined test weight and packing adjustments were 1.065, 1.071, and 1.065). These combined for a total estimated inventory of 2,289.3 t. The mass of grain removed from the individual bins was not tracked, but a comparison can be made based on the total sold from the facility. The facility total was 2,286.3 t at the time inventory was measured, resulting in an over prediction of 0.13%.

Limitations

Though the system developed for determining the volume of irregular-shaped grain surfaces improved the volume estimation in a number of scenarios, the system was not without limitations. Dust suspended in the air in the headspace between the distance meter and the grain surface caused the laser distance measurements to fail intermittently when bins were measured shortly after filling. Ideally, the bin measurement system should be able to measure the entire bin



(a) (b)

Figure 7. Example fill scenarios: (a) rendering of initial fill geometry, (b) surface generated by the system after partial unloading.

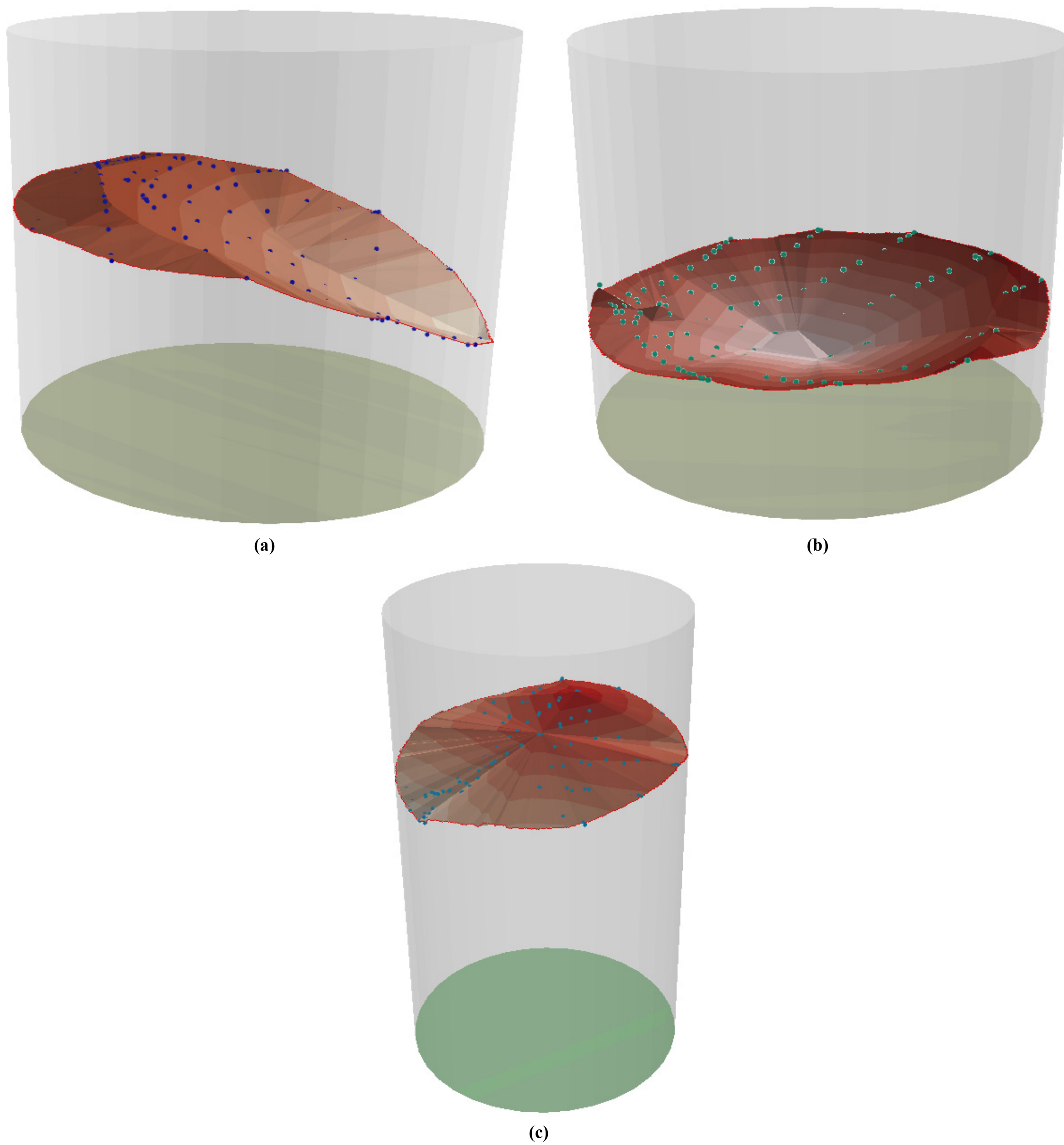


Figure 8. Further examples of the system applied to a farm storage system: (a) side draw in a 14.6 m diameter bin, (b) inverted cone in a 14.6 m diameter bin, and (c) off centered partial cone in a 4.6 m diameter bin

wall/grain surface interface. However, if the system's field of view was obstructed, a limited number of points were obtained along the interface. This was most frequently encountered when bins were very full and the surcharge cone of grain exceeded the eave height of the bin. For this condition the model was unable to bound the points and locate the center point. Additionally, for a peaked bin, if the opposite side of the cone was not visible, then surface interpolation had no way to capture the topography. This occurred in bins that were relatively full, or as seen in figure 7a, where discharge through a side draw opposite the manhole was used.

The method presented here is best suited for conditions where the surface topography is difficult to estimate using traditional methods, or where a large fraction of the total volume is represented by the surface. While extra time is required to collect and process the data, this method does account for irregularities in the surface conditions of the grain. Processing the data required that the point cloud generated be visually inspected in ArcScene to remove any erroneous points that captured obstructions in the bin (steel supports, temperature cables, etc.). This limited the ability to automate or batch process measurements taken from multiple bins.

CONCLUSIONS

Based on the need to develop a portable system to accurately define the grain surface, a bin measurement system was developed that utilized a laser distance meter to generate a low density point cloud representation of the grain surface. Primary conclusions from this study are:

- Data processing methods were developed that allowed complex grain surfaces to be modeled.
- The volume of grain in a bin could be estimated from the bin geometry and the generated surface.
- Data processing could not be automated due to the need to visually inspect and manually post-process the data.
- Proper application of the system required a clear view of the entirety of the grain surface.

ACKNOWLEDGEMENTS

The research was supported by the USDA (CRIS No. 5430-43440-007-08R and RMA Agreement No. 09-IA-0831-0096). This is publication No. 15-05-073 of the Kentucky Agricultural Experiment Station and is published with the approval of the Director. This work is supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, Hatch- Multistate under 1002344. The assistance provided by Will Adams, Drew Schiavone, and Carla Rodrigues (University of Kentucky) in the development of the measurement system is highly appreciated. Additionally, the authors would like to thank Chuck Kunisch (Michigan Agricultural Commodities, Brown City, Mich.) and Andy Shaffner (Shaffner Brothers Farm, Midland, Mich.) for allowing us to use their facilities to conduct this research.

REFERENCES

Bhadra, R., Turner, A. P., Casada, M. E., Montross, M. D., Thompson, S. A., Boac. J., M., ... Maghirang, R. G. (2015). Pack factor measurements for corn in grain storage bins. *Trans. ASABE, 58*(3), 879-890. doi:http://dx.doi.org/10.13031/trans.58.11033

Bhargava, N., Bhargava, R., & Tanwar, P. S. (2013). Triangulated irregular network model from mass points. *Int. J. Adv. Comput. Res., 3*(2), 172-176.

Erdogan, S. (2009). A comparision of interpolation methods for producing digital elevation models at the field scale. *Earth Surf. Process. Landforms, 34*(3), 366-376. http://dx.doi.org/10.1002/esp.1731

ESRI. (2012). What is a time surface? ArcGIS Resour. Retrieved from http://resources.arcgis.com/en/help/main/10.1/index.html#//006000000001000000

McNeill, S. G., Montross, M. D., Thompson, S. A., Ross, I. J., & Bridges, T. C. (2008). Packing factors of feed products in storage structures. *Appl. Eng. Agric., 24*(5), 625-630. https://doi.org/10.13031/2013.25260

Oliver, M. A., & Webster, R. (1990). Kriging: a method of interpolation for geographical information systems. *Int. J. Geogr. Information Syst., 4*(3), 313-332. http://dx.doi.org/10.1080/02693799008941549

Thompson, S. A., & Ross, I. J. (1983). Compressibility and frictional coefficients of wheat. *Trans. ASAE, 26*(4), 1171-1176. http://dx.doi.org/10.13031/2013.34099

Thompson, S. A., McNeill, S. G., Ross, I. J., & Bridges, T. C. (1987). Packing factors of whole grains in storage structures. *Appl. Eng. Agric., 3*(2), 215-221. https://doi.org/10.13031/2013.26677

Thompson, S. A., Schwab, C. V., & Ross, I. J. (1991). Calibration of a model for packing whole grains. *Appl. Eng. Agric., 7*(4), 450-456. https://doi.org/10.13031/2013.26244

Turner, A. P., Montross, M. D., Jackson, J. J., McNeill, S. G., Casada, M. E., Boac, J. M., ... Thompson, S. A. (2016a). Error analysis of stored grain inventory determination. *Trans. ASABE, 59*(3), 1061-1072. http://dx.doi.org/10.13031/trans.59.11501

Turner, A. P., Montross, M. D., McNeill, S. G., Sama, M. P., Casada, M. E., Boac, J. M., ... Thompson, S. A. (2016b). Modeling the compressibility behavior of hard red wheat varieties. *Trans. ASABE, 59*(3), 1029-1038. http://dx.doi.org/10.13031/trans.59.11432