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ABSTRACT

Use of automated machine guidance (AMG) that links sophisticated design software with construction equipment to direct the operations of construction machinery with a high level of precision, has the potential to improve the overall quality, safety, and efficiency of transportation construction. Many highway agencies are currently moving towards standardizing the various aspects involved in AMG with developing the design files to implementing them during construction. In this paper, two aspects of AMG and their impacts on earthwork operations are discussed. The first aspect deals with the estimation of earthwork quantities and its impact on productivity on costs. The second aspect deals with the factors contributing to the overall accuracy of AMG. These two aspects are discussed in this paper using survey responses from various AMG users (contractors, agencies, software developers, and equipment manufacturers) and some experimental test results. Both these aspects are critical to understand during implementation of AMG as these have productivity and cost implications to the users.

Keywords: automated construction—earthwork quantities—accuracy—specifications—GPS—AMG

INTRODUCTION

Currently, highway agencies are improving electronic design processes that support construction with automated machine guidance (AMG) and deliver higher quality products to the public. Equipment providers are rapidly advancing software tools and machines systems to increase automation in the design and construction process. Motivation to more widely adopt AMG processes therefore exists. However, the framework for adoption of AMG into the complex framework of design to construction has not been fully developed. Technical, equipment, software, data exchange, liability/legal, training, and other barriers, limits progress with AMG implementation into construction projects. To address these issues, a national level study was initiated by the Transportation Research Board as the National Cooperative Highway Research Program (NCHRP) 10-77 study.

In this paper, two specific aspects of AMG that directly influences the earthwork operations are discussed. The first aspect deals with earthwork quantity estimation using AMG. The second aspect deals with accuracy of AMG and the various factors that contribute to errors in the AMG process. Both these aspects are critical to understand in a practical perspective as these have productivity and cost implications to the contractors and agencies. In the following, each of these aspects are separately discussed by presenting results of a national survey conducted with over 500 participants from agencies, contractors, equipment vendors, software vendors, and some experimental tests conducted by the authors. Survey results of selected questions are presented herein for brevity, and all results are available in White et al. (2015).

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EARTHWORK QUANTITY ESTIMATION

Earthwork pay items are historically objects of great dispute between agencies and contractors. Proper use of digital information for AMG will likely result in less confusion and more accuracy than traditional methods of earthwork pay item quantification and payment. According to the survey responses (see White et al. 2015), a majority of the survey responding contractors currently use DTMs for estimating quantities, means and methods, constructability, quantity of the progress of work, and payment. Earthwork pay quantification from AMG must include mechanisms that all parties in the contract (both the agency-owner and the contractor) can trust. The efficient use of digital information in AMG applications typically involves creation of a digital terrain model (DTM) during initial planning, which is then passed to the design phase for addition of design data in a 3D model. This facilitates efficient computation and measurement of earthwork quantities for use during the procurement phase (bidding). Finally, the construction phase involves verification of project as-built quantities.

Impact of AMG on Productivity Gain and Cost Savings

Figure 1 presents responses from contractors and vendors on the impact of AMG on productivity gain and project cost savings. A majority of the equipment vendors indicated potential productivity gain of about 40% and potential cost savings of about 25 to 40% using AMG. On the other hand, a majority of the contractors indicated potential productivity gain of about 10 to 25% and potential cost savings of about 10 to 25% using AMG. Productivity gain and cost savings reported in the literature on earthwork construction projects using AMG is also presented in Figure 1 (Jonasson et al., 2002; Aðalsteinsson, 2008; Forrestel, 2007; Higgins, 2009; Caterpillar, 2006).

Jonasson et al. (2002) reported productivity gain and cost savings information for a fine grading project using a motorgrader with different position measurement technologies (i.e., ultrasonic's, 2D and 3D lasers, and GPS). The productivity gain ranged from about 20 to 100% and cost savings ranged from about 15 to 40%, depending on the position measurement technology used. The cost savings were due to a reduction in surveying support and grade checking, an increase in operational efficiency, and a decrease in number of passes. Their study indicated that the 3D laser systems required a direct line of sight to the equipment while the GPS systems did not, which resulted in a small increase in fleet productivity and a decrease in unit cost using GPS guidance systems over 3D laser systems.

Aðalsteinsson (2008) reported results from a field demonstration project conducted using an excavator to excavate a trench with 1650 cubic yards of sandy gravel material. In his study, the AMG approach showed a productivity gain of about 25% over a no AMG approach. Caterpillar (2006) reported results from a field demonstration project conducted in Spain by constructing two 80 m identical roads: one road with AMG on construction equipment and the other with similar equipment but using conventional methods and no AMG. AMG was used for bulk earth moving and fine grading work. An overall productivity increase of about 101%, fuel cost savings of about 43%, and increased consistencies in grade tolerances were reported for this project.

The results from these field case studies and survey responses indicate that the productivity gain and cost savings using AMG on earthwork projects can vary significantly (with productivity gains in the range of 5% to 270% and cost savings in the range of 10% to 70%). This variation is most likely because of various contributing factors, such as project conditions, materials, application, equipment used, position measurement technologies used, and operator experience.

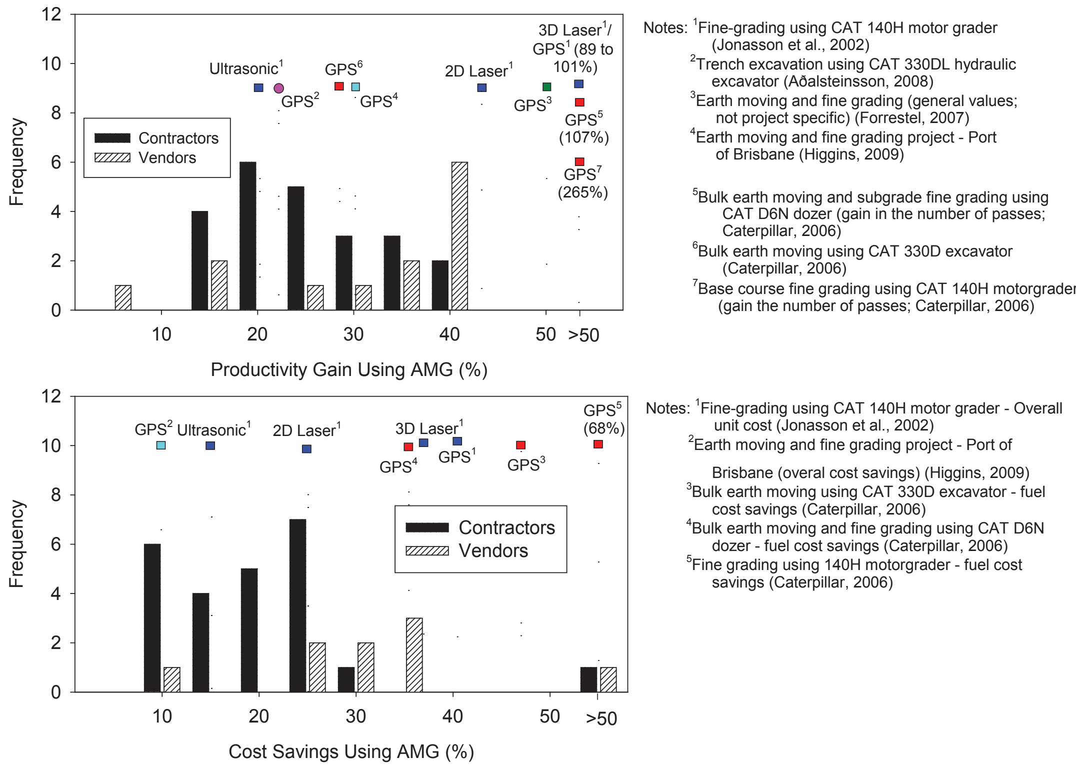

Figure 1. Survey Responses by Contractors and Vendors and Productivity Gain and Potential Cost Savings using AMG, and Data obtained from Field Case Studies

Earthwork Quantity Computation and Measurement

Accuracy of DTMs

Survey results reported by White et al. (2015) indicated that a majority (> 70%) of contractors, software/hardware vendors, and agencies who responded believe that the number of elevation data points used in creating the DTM is an important factor in the accuracy of the DTM. Evaluating the accuracy of DTMs by comparing them to the actual surface is a challenging and expensive task.

Various interpolation methods are available in the literature for generating contour grid data for DTMs, which include: (a) inverse distance to power; (b) Kriging; (c) local polynomial; (d) minimum curvature; (e) nearest neighbor; and (f) triangulated irregular network (TIN). To study the influence of the number of data points, three different data sets, with 78, 38, and 11 data points, were captured over a 540 m^2 area. The area consisted of a sloping terrain with an elevation difference of about 3.5 m over 60 m length. DTMs were generated using the six different interpolation methods described above. DTMs generated from 78 data points are presented in Figure 2.

The accuracy of each DTM that used 78 data points was evaluated using a cross-validation technique. This technique involved taking out a known data point from the data set, estimating the point using the model, and comparing the estimated value with the actual one. This process was repeated for all 78 data points. An absolute mean error (calculated as the average of absolute value of the difference between the actual and the estimate value) was then calculated for each interpolation method, as summarized in Table 1.

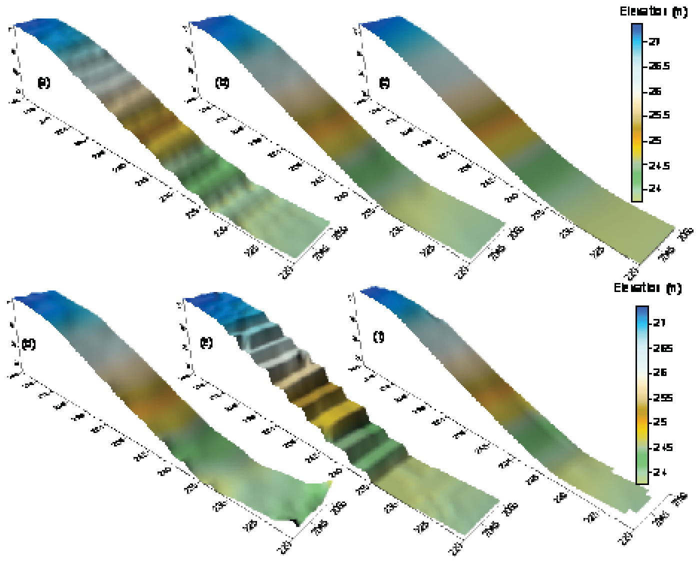

Figure 2. DTMs of a 540m^2 area using 78 elevation data points using different interpolation methods: (a) inverse distance to a power; (b) kriging; (c) local polynomial; (d) minimum curvature; (e) nearest neighbor; (f) TIN

Table 1. Absolute mean error of estimated elevation data based on cross-validation process using different interpolation methods

Data Interpolation Method	Estimated Elevation Absolute Mean Error (mm)
Inverse distance to power	100
Kriging	20
Local polynomial	70
Minimum curvature	50
Nearest neighbor	40
Triangulated irregular network (TIN)	30

For this data set, results indicated that the Kriging method is the most accurate method with 0.02 m absolute mean error. The TIN method showed a slightly higher absolute mean value of 0.03 m. The grid generated using the Kriging method with 78 data points was then considered as a “true” representative surface, and it was used as a comparison to the grid data generated using the other interpolation methods, as summarized in Table 2. The Kriging method produced absolute mean error of 0.02 m using 38 data points and 0.05 m using 11 data points. The TIN method produced slightly higher absolute mean error values. Minimum curvature, local polynomial, and inverse distance to power methods produced greater absolute mean error values, compared to the TIN method. The nearest neighbor method could not replicate the surface terrain, as it doesn’t interpolate the data, which is clearly a limitation of the method.

It is important that existing surfaces are portrayed as accurately as possible, so the model can be passed ahead to the design, estimation, bidding, and construction phases of the project with high fidelity. A proper understanding of the factors that influence the accuracy of the DTM is important to understand and must be addressed during the model development phase.

Table 2. Absolute mean error of estimated elevation data by comparing Kriged DTM with 79 points with different interpolation methods

	Estimated Elevation Absolute Mean Error (m)		
Data Interpolation Method	**79 Data Points**	**38 Data Points**	**11 Data Points**
Inverse distance to power	0.06	0.10	0.11
Kriging	0.00	0.02	0.05
Local polynomial	0.06	0.07	0.07
Minimum curvature	0.03	0.04	0.09
Nearest neighbor	0.06	0.12	0.24
Triangulated irregular network (TIN)	0.01	0.04	0.06

Computation of Earthwork Quantities

Earthwork quantities are traditionally computed using the average-end-area method, which is based on averaging the areas of two consecutive cross-sections and multiplying the average by the distance between them (Burch, 2007). A polar planimeter is typically used by surveyors to measure the area by tracking the boundaries.

Using DTM, the surface-surface method can be used to compute quantities, by overlapping the existing terrain and the design DTM surfaces. The U.S. Army Corps of Engineers (2004) provides a detailed explanation of the surface-surface quantity estimation method using TIN surfaces. Many software applications (including Microstation and Autodesk) now have the capability to easily compute quantities using the surface-surface method. The accuracy of the generated DTM, as described above, plays a significant role in the estimated earthwork quantities. Soil shrink-swell factors also affect to the overall quantity estimation, which are dependent on the soil type, so they must be selected appropriately (Burch, 2007).

Vonderohe et al. (2010) reported that differences between average-end-area and surface-surface increases as the cross-section levels increase, although the relationship is not linear. As the cross-section intervals decrease, the computations become theoretically the same. The differences are observed to be as great as 5% when 100 ft cross-section intervals are used with the average-end-area method. Such differences can contribute to significant cost discrepancies for large projects. The advantage of using DTMs is that earthwork quantities can be computed “on the fly,” as the model is being developed, and also during construction. Various layers and volumes that represent various bid items and various costs can be collected and categorized during the design process. Designed surfaces are accurately portrayed and can be passed ahead in the AMG process with high fidelity.

Model Enhancement for Construction Purposes

Model enhancement might be necessary during the development process for certain aspects, such as providing offsets between pavements and subgrades, delineating areas where equipment operation is excluded, and correcting inconsistencies that are not problematic for design models but are for AMG. The benefits of this work phase are that the constructor may discover possible design improvements or design errors in the model, which can end up saving time and money during construction. The constructor may develop a better understanding of how to construct the project as the design model is enhanced. The constructor could improve construction productivity and safety by adding exclusion zones for equipment and methods to track equipment usage during construction.

Model Conversion to AMG Format

It may be possible to develop automatic load counts and infer earthwork or pavement volume or tonnages moved by equipment using onboard weight detection. A data collection method could be developed to infer current elevations of partially-completed projects by knowing current equipment elevations. This information may be used to monitor current earthwork volumes for partial payment.

Model Conversion to QA/QC Format

QA/QC personnel can potentially use DTM and the final design model to automatically locate test locations and display results. Elevations of existing surfaces can be obtained quickly and modeled in 3D to estimate current earthwork and pavement volumes or tonnages for partial payments. Quality information is processed along with volume information to ensure that partial payments are made for earthwork or pavement that meets quality requirements.

Limitations

The limitations in all of the above, however, include potentially higher up-front costs for software, hardware, and highly-trained personnel, and the possible inability to make gut-level checks for some types of design errors. Downstream personnel may be critical of design personnel for alternative designs that were not used and documented in unused parts of the model. Designers may consider inspection of the details of the design process by downstream personnel to be too invasive of their professional autonomy.

ACCURACY OF AMG PROCESS DURING CONSTRUCTION

The accuracy of the AMG process during construction is primarily influenced by three variables: (a) position measurement technology; (2) construction processes; and (c) human errors.

Survey responses from surveyors and planners indicated total station surveying (robotic and conventional) is considered more accurate than GPS and photogrammetric surveying. Manufacturers and researchers have published the precision and accuracy values of various position measurement technologies in the technical literature (Peyret et al., 2000; Retsher, 2002; Barnes et al., 2003; Mautz, 2008; and Trimble, 2008).

It does not appear that the effect of construction process and human errors has ever been thoroughly studied or quantified. Most contractors, vendors, and agency personnel who responded to the survey questions reported that these variables play a major role in the overall accuracy of the AMG process.

Position Measurement Technologies

Table 3 provides a summary of accuracy, coverage range, measurement principle, and relative cost of different position measurement technologies that are typically used in construction applications. The laser or ultrasonic technologies offer higher vertical (elevation) accuracies than GPS and have shown success in achieving tighter tolerances on some fine grading projects (Daoud, 1999). However, laser or ultrasonic technologies have some practical limitations with use in rain, dust, wind, and snow, and need frequent charging of deep cell batteries (Cable et al., 2009). These technologies also require a direct line of sight between the control station and the receiver on the equipment, which is why they have not been used on heavy earth moving equipment, other than motor graders (Jonasson et al., 2000).

GPS-based technologies can overcome the limitations stated above with laser and ultrasonic technologies, but they don't offer high vertical accuracy. Peyret et al. (2000) noted that RTK GPS systems normally have vertical accuracy (±2 cm) or twice the horizontal accuracy (±1 cm). A vertical accuracy level of ±2 cm is not sufficient for applications such as paving or fine grading. Another common problem reported with GPS-based technologies is limited availability of satellites (and, consequently, poor signal attenuation) when operating close to structures, trees, or underground environments. Currently, the U.S. Air Force is committed to maintaining availability of 24 operational GPS satellites, 95% of the time (U.S. Air Force 2014) and is projecting for increased number of satellites in the future. The relative gain in accuracy from an increased number of satellites may be marginal (Hein et al. 2007), however, AMG users can expect to increase the chances of having the minimum number of satellites required to achieve a certain amount of accuracy because of the new additional satellites.

Recent advancements with use of HA-NDGPS with initiatives from FHWA, globally positioned GDGPS and IGS technologies is providing opportunities to achieve cm level accuracy without significant on-site investment. U.S. Air Force is currently in the process of developing and launching a next-generation GPS satellite (GPS III) which will be available for all military and civilian applications with improved accuracies (U.S. Air Force 2014).

GPS with laser or ultrasonic augmentation offers improved vertical accuracies (2 to 6 mm) (Trimble, 2008). From recent field studies on concrete paving projects in Iowa, Cable et al. (2009) found that laser-augmented GPS measurements are somewhat capable of guiding the paver and controlling elevation to achieve a reasonable profile for low-volume roads, but recommended that improvements (or fine tuning) in software is required to better control the elevation that will result in smoother surface profiles.

Construction Process and Human Errors

The overall accuracy of the AMG process includes these construction process parameters: (a) speed of operation; (b) direction of travel; (c) terrain; and (d) material type and support conditions (uniformity). These parameters have not been thoroughly studied or documented in the technical literature and they are application-specific or machine-specific. A statistical approach to quantify the influence of these factors on the overall accuracy of the AMG process is presented in White et al. (2015).

The level of impact for each of these factors differs with the application type. Speed of operation affects AMG accuracy and overall project costs. Increasing speed decreases the ability of machines to react to error signals and, consequently, reduces the accuracy of the measurement. However, productivity declines as speed declines, impacting project costs. The effect of speed of operation is clearly interlinked with the abilities of the position measurement technology feedback response time. The terrain on a job site can have an impact. Although not critical for paving and fine grading applications, terrain can be critical for general earthwork and excavation applications.

The type of material and support conditions under the equipment (whether stable or unstable, uniform or non-uniform) impacts the overall accuracy. Unstable or non-uniform support conditions under the equipment make it more difficult to maintain control relative to the reference. This factor can play a critical role in paving and fine grading applications, and may not be as critical for general earthwork and excavation applications.

Table 3. Summary of Different Position Measurement Technologies

System	Accuracy	Range	User Cost	Reference
Conventional GPS (no corrections)	Variable, > 5 m	Global	Low	DoD, 2008
Assisted GPS (via mobile phones)	Variable, 2 to 10 m	Global	Low	Mautz, 2008
GPS integrated with INS	Variable	Global	Variable	Mautz, 2008
Wide Area Augmentation System (WASS) or Satellite Based Augmentation System (SBAS)	1.6 to 3.2 m horizontal and 4 to 6 m vertical	Global	Low	FAA, 2008
Nationwide differential GPS (NDGPS)	1 m within 150 km of the broadcast site	Global	Low	ARINC Inc., 2008
HA–NDGPS	10 cm horizontal and 20 cm vertical	Global	Low – currently in development	FRP, 2012
Global DGPS	10 cm horizontal	Global	Low	NASA, 2014
International GNSS Service (IGS)	<10 cm horizontal and vertical	Global	Low	Moore, 2007
RTK GPS	cm	Global	Moderate to high	Mautz, 2008
Locata (pseudolites)	6 mm	2 to 3 km	High	Barnes et al., 2003
Laser- augmented GPS	3 to 6 mm	300 m/line of site radius of laser source	Moderate to high	Trimble, 2008
Laser	±2 mm		Low to moderate	Retscher, 2002
Robotic total station	±2 mm	700 m/line of site radius of source	High	Retscher, 2002
Ultrasonic	±1 mm	Immediate reference	Low to moderate	Trimble, 2008
Ultrasonic augmented GPS	±1 mm	Immediate reference	Moderate to high	Trimble, 2008
Infrared laser	0.1 to 0.2 mm	2 to 80 m	High	Kraut-Schneider, 2006

SUMMARY OF KEY FINDINGS

Impacts of AMG on Earthwork Quantities

- Earthwork pay quantification from AMG must include mechanisms that all parties to the contract (both the agency-owner and the contractor) can trust.
- The accuracy of the generated DTM plays a significant role in the estimated earthwork quantities. Experimental test results documented herein indicated that the interpolation model and the number of data points both affect the accuracy of the DTM.
- Model enhancement might be necessary during the development process for certain aspects, such as providing offsets between pavements and subgrades, delineating areas

where equipment operation is excluded, and correcting inconsistencies that are not problematic for design models but are for AMG.
- The results from case studies described in the literature and survey responses indicate that the productivity gain and cost savings using AMG on earthwork projects can vary significantly because of various contributing factors, such as project conditions, materials, application, equipment used, position measurement technologies used, and operator experience.
- It is important that existing surfaces are portrayed as accurately as possible, so the model can be passed ahead to the design, estimation, bidding, and construction phases of the project with high fidelity. A proper understanding of the factors that influence the accuracy of the DTM is important to understand and must be addressed when developing the model.

Accuracy of AMG Process

- AMG component accuracies is an issue that affects various stages of the process including: Initial data collection for developing existing surface terrains; development of DTM and EED, AMG processes, procedures, and end-user competencies, QA/QC reported practices, heavy and fine grading equipment operations, and paving equipment operations.
- A common problem reported with GPS-based technologies is limited availability of satellites (and, consequently, poor signal attenuation) when operating close to structures, trees, or underground environments. Currently, the U.S. Air Force is committed to maintaining availability of 24 operational GPS satellites, 95% of the time and is projecting for increased number of satellites in the future. While the relative gain in accuracy from an increased number of satellites may be marginal (Hein et al., 2007), AMG users can expect to increase the chances of having the minimum number of satellites required to achieve a certain amount of accuracy because of the new additional satellites.
- The overall accuracy of the AMG process includes various construction process parameters: speed of operation, material type and support conditions (uniformity), and terrain. These parameters have not been thoroughly studied or documented in the technical literature and they are application-specific or machine-specific.

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