GEORGIA DOT RESEARCH PROJECT 16-18

FINAL REPORT

ASSESSMENT OF CONSTRUCTION POINTS FOR GRADE CONTROL AND REFERENCE IN 3D

OFFICE OF PERFORMANCE-BASED MANAGEMENT AND RESEARCH

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The objective of this research is to investigate the causes of inaccuracies of grade elevations from current practices and identify best practices for grade control and referencing on transportation infrastructure construction projects in Georgia. A nationwide questionnaire survey was conducted with contractors, engineers, surveyors, and owners, and the following causes of the discrepancies are identified: (1) long time gap between design and construction phases; (2) poor techniques in surveying; and (3) long interval between survey points. Through an actual case study with an ongoing highway construction project, the following conclusions and recommendations are made: (1) a mandatory field survey before earth moving is recommended; (2) unmanned aerial vehicle (UAV) and Mobile Mapping System (MMS) are effective for 3D grade control in planning and site cleaning phases; (3) terrestrial laser scanning (TLS) is appropriate for 3D grade control in a subgrade grading stage; and (4) robotic total station (RTS) is recommended for the final grading stage.</td></tr>
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GDOT Research Project 16−18

Final Report

ASSESSMENT OF CONSTRUCTION POINTS FOR GRADE CONTROL AND REFERENCE IN 3D

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EXECUTIVE SUMMARY

The Georgia Department of Transportation (GDOT) currently requires construction inspectors to verify elevations through traditional survey methods, including a total station for location data and leveling or string-lining for elevation data. Contractors on GDOT projects are permitted to utilize various technology aides for grade control and location references, including survey data, Global Positioning System (GPS), and laser scanning as long as those points are verified by GDOT inspectors. In many cases, however, GDOT construction projects have experienced the negative impacts resulting from the lack of interoperability of various technological systems deployed to accomplish grade control and references. These negative impacts include increased project costs from material overrun as well as increased project schedules due to construction re-work. Furthermore, GDOT construction inspectors are unable to verify these points without greatly impacting the construction schedule due to limited resources and personnel. Therefore, the objectives of this research are to 1) identify which current practices or technologies cause the major disagreement of measurement (e.g., elevation) and 2) establish best practices for grade control and referencing for transportation infrastructure construction projects in GDOT. Research results include updated and more detailed guidelines dealing with grade control and referencing on earthwork and infrastructure projects. To achieve the objectives, the research team conducted four main tasks as follows.

- **Task 1. Literature reviews**: The initial goal is to capture as much information as possible from the grade control operations currently taking place at GDOT road

construction sites as well as from other state DOTs' documented grade control strategies. For this purpose, the research team reviewed existing standards, specifications, research outcomes, and publications related to grade control and reference on transportation infrastructure construction projects. In addition to GDOT, the research team reviewed documented materials from other state DOTs to identify what measures are taken for grade control and referencing.

- **Task 2. Lessons learned from past construction projects in GDOT**: In this task, the lessons learned from past GDOT construction projects were extensively studied. Through documented project information and interviews with GDOT inspectors or project managers, the research team focused on identifying the following: 1) various survey methods used by contractors, 2) any cases of measurement discrepancies (type of project, location, causes, technologies used), and 3) interoperability problems among different measurement methods (e.g., file formats and compatibility among different software tools).
- **Task 3. Active case studies in GDOT**: An actual case study with GDOT's active road construction projects was conducted. The intent is to identify the causes of discrepancy measurements directly from active projects based on the knowledge obtained from the previous tasks. For this purpose, the research team developed a framework to detect the measurement discrepancy through the comparison of 3D surface models between an as-designed model and an as-built model. Moreover, the research team applied several data collecting tools such as robotic total station (RTS), terrestrial laser scanning (TLS), unmanned aerial vehicles (UAVs), and a mobile laser scanning robot as a representation of a mobile mapping system

(MMS) to investigate the best tools for efficiently generating a 3D surface model at each grading stage.

- **Task 4. Develop best practice guidelines**: Based on the findings from the lessons learned and case studies with an ongoing project in the previous tasks, the recommendations to prevent the identified causes of inaccuracies between the design and the final field grade were developed. The research team had interviews and an online survey with survey companies, DOT engineers, and contractors to discuss best practices for the grade control and referencing for the highway construction. With the results of the interviews, surveys, and case studies, the team developed the best practice guidelines for grade control and references on GDOT transportation infrastructure construction projects.

Through the past case studies, the research team identifies that three main causes of inaccuracies are 1) long time gap between design and construction phases, 2) poor techniques in surveying, and 3) long interval between survey points. Moreover, the online survey results show that most discrepancies were found before earth moving (47%) and before grading (29%), and most causes were survey errors in the design phase (35%) and construction phase (23%). Therefore, the following is recommended: 1) check control points before earthwork; 2) inspect the earthwork surface elevation before grading; and 3) utilize new field survey practices collecting 3D dense points from the surfaces. Through the actual case study in GDOT, the research team concludes that UAV and MMS are the most efficient tools for 3D grade control of cleared surfaces. In addition, TLS is recommended for 3D grade control of subgrade graded surfaces because it satisfies the grade tolerance of 0.5’. RTS, which can meet the grade tolerance of 0.25’ for final surfaces, is recommended for the final surface paving.

Through a series of the tasks, the following recommendations are made: 1) re-adjust the control points installed in a design phase before earth moving; 2) collect dense surface points to generate a continuative 3D surface model; 3) use UAV or MMS to generate a 3D surface model for cleared surfaces; and 4) use TLS for the subgrade grading and RTS for the final surface paving. Another outcome of this research is providing the best-practice guidelines in 3D grade control for each grading stage. With the proposed best practice guidelines, the research team expects that elevations and locations of construction items could more accurately reflect design values. Moreover, GDOT can experience financial benefits by resolving the issues of decreased material overruns and project time extensions due to grade control inaccuracies.

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1. Introduction

Several researchers have studied the impact of positioning and localization technologies on construction, specifically Global Positioning System (GPS) and laser scanning for productivity on earthwork operations and infrastructure projects (Du and Teng 2007; Navon 2005; Wang and Cho 2015). The Wisconsin Department of Transportation conducted an exploration to implement GPS as a controlling tool for highway maintenance equipment, including motor graders, dozers, and asphalt pavers (Vonderohe 2007). Terrain models for design and construction plans have been created through various measurement technologies and grade control mechanisms (Georgia Department of Transportation 2018). Navon and Shpatnitsky (2005) identified a need for better monitoring and controlling road construction progresses through several case-studies of construction projects and resulting inaccuracies of grade elevations.

The Georgia Department of Transportation (GDOT) currently requires construction inspectors to verify elevations through traditional survey methods including a robotic total station (RTS) for location data and leveling or string-lining for elevation data (Georgia Department of Transportation 2018). Contractors on GDOT projects are permitted to utilize various technology aides for grade control and location references, including survey data, Global Positioning System (GPS), and laser scanning as long as those points are verified by the GDOT inspectors (Georgia Department of Transportation 2013). In many cases, GDOT construction projects have experienced the negative impacts resulting from the lack of interoperability of various technological systems deployed to accomplish grade control and references. These negative impacts include increased project costs from material overrun as well as increased project schedules due to construction re-work. Furthermore, the GDOT construction inspectors are unable to verify these points without greatly impacting the construction schedule due to limited resources and personnel. Therefore, there is a strong research need to 1) identify which current practices or technologies cause the major disagreement of measurement (e.g., elevation) and 2) establish best practices for grade control and referencing for transportation infrastructure construction projects in GDOT.

The purpose of this research is to investigate the causes of inaccuracies of grade elevations from current practices and identify best practices for grade control and referencing on transportation infrastructure construction projects in Georgia. In this study, the following research tasks were conducted: 1) literature reviews; 2) lessons learned from past construction projects in GDOT; 3) case studies with an ongoing highway construction project; and 4) the best practice guidelines development.

2. Literature Review (Task 1)

In this task, the research team reviewed existing standards, specifications, research outcomes, and publications related to grade control and reference on transportation infrastructure construction projects. One subsection of this review included the specifications for an evaluation of GDOT's existing grade control and transportation infrastructure construction projects in which these specifications have been applied. In addition to GDOT, the research team also reviewed documentations from other state

DOTs to identify what measures are taken for grade control and referencing. Moreover, several technical papers related to this research were also reviewed.

2.1 Specifications and manuals

Firstly, identifying GDOT's discrepancy criteria was the initial main focus for this study. Plus, the criteria of construction point discrepancy from other states were reviewed as well. According to the GDOT Automated Survey Manual (Georgia Department of Transportation 2018), a route survey in the road planning stage should be controlled within the tolerance of 0.1' for road surfaces and 0.5' for ground terrain surfaces. In addition, the Standard Specifications Construction of Transportation (2013) inspectors established the grade tolerance of 0.5' for subgrade surfaces and 0.25' for final surfaces. The grade tolerance is slightly different in each state. Table 1 lists the survey tolerances in GDOT, and Figure 1 shows the grade tolerances regulated in other states. The research team also reviewed construction survey manuals in several states. The team found that many states suggest conventional methods (e.g., grade stakes) for the grade elevation control, and some states have authorized the use of GPS controlled graders.

TABLE 1
Survey tolerances in GDOT Automated Survey Manual

Types	Tolerances
Traverse	1:20000 rural, 1:25000 urban
Leveling	Square Root of miles ran x .049'
Control points	0.03' horizontally, 0.02' vertically
Route survey	0.50' ground, 0.10' pavement

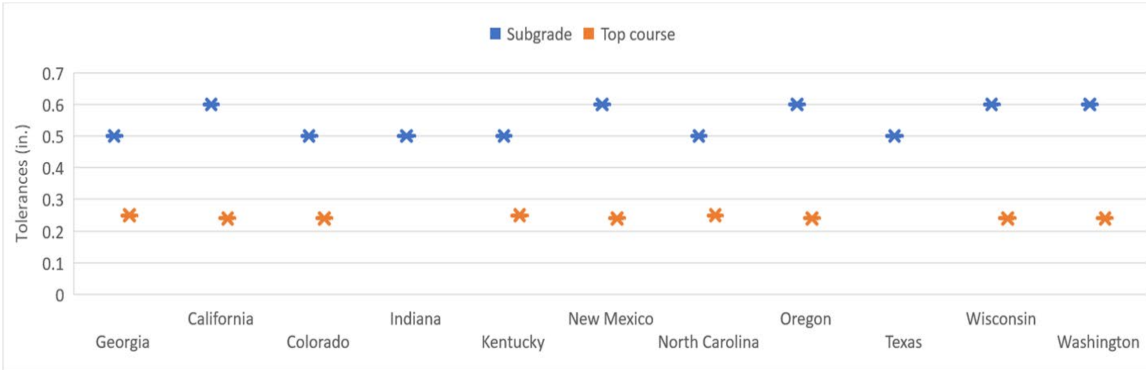


FIGURE 1
Grade tolerances in other states

Several research papers related to this topic were reviewed. The implications of this literature review are that the factors causing the discrepancies can be classified into two kinds of factors: human factors and technical factors (Arain et al. 2004). According to Arain et al. (2004), the human factors causing the discrepancies include lack of coordination, mutual respect, and communication, and the technical factors include lack of skilled manpower, interoperability, and details in drawings. Slattery and Slattery (2013) proposed a 3D grade control method using terrestrial laser scanning (TLS). They introduced that TLS is a feasible means for controlling the grade of road construction projects because it can generate more accurate and more precise 3D layouts than conventional survey methods. Through the literature reviews, the research team found that the road grade elevation has strict tolerance requirements, but the current practices with conventional methods often cause grade discrepancies between design and as-built outcomes. Thus, a more efficient approach to measure and monitor the road grades during the construction project stages is needed, and the team investigated the state of the practices on 3D grade control.

2.2 State of the practices on 3D grade control

This research reviewed the current state of practices in generating 3D models using dense point clouds for 3D grade control in road construction projects. In recent decades, two major instruments have been applied to the collection of 3D geometric data, including TLS, and unmanned aerial vehicles (UAVs) and several novel geo-referencing methods for each instrument.

2.2.1 TLS

TLS is a famous tool for collecting a large amount of 3D data with high accuracy and density. Within a second, TLS can acquire one million points with a point density of ± 2 millimeters in 10 meters. However, since TLS measures the relative distance between objects, geo-referencing is required to obtain the absolute coordinates of the points. Typical geo-referencing methods are classified into two types: 1) direct geo-referencing and 2) indirect geo-referencing.

Direct geo-referencing

TLS can be directly georeferenced by placing the optical center of the sensor on a known point and then orienting the intrinsic reference system (IRS) toward a known point (Scaioni and Polo 2005). Although this method has an advantage in that it can apply the absolute coordinates of all the scanned points in a single adjustment process, it requires sophisticated adjustment work. Another method for direct geo-referencing is to use GPS and an inertial measurement unit (IMU) (Reshetyuk 2009). Paffenholz et al. (2010) examined a direct geo-referencing approach for TLS using multi-sensors, including two sets of GPS antenna and IMU. Although this method can eliminate the time needed to measure ground control points, the accuracy of the generated point cloud does not satisfy the required tolerance for the subgrade construction due to the errors produced by GPS and IMUs (Alba et al. 2007).

Indirect geo-referencing

Indirect geo-referencing is a way to compute a transformation matrix with pre-measured targets or benchmarks. In general, the indirect geo-referencing approach provides better results than direct geo-referencing (Mukupa et al. 2017). At least three known points are required to calculate the transformation matrix. In many cases, the geo-referencing process is conducted after registering all scans to reduce the number of targets required for geo-referencing. However, during the registration of long-strip scans, registration errors can easily accumulate along the strip (Zheng et al. 2016) . To reduce these accumulative errors, Zheng et al. (2016) proposed a Random Sample Consensus (RANSAC)-based registration approach that makes closed loops. However, this method requires more than two lines of scanning pairs, which can be time-consuming. To resolve the accumulative error problem, this project adopted a resection-based registration approach using three known points to compute the position and azimuth of each scan. Since this approach does not require a point cloud registration process, the accumulative error that occurs while registering consecutive point clouds in the longitudinal direction does not need to be considered.

2.2.2 UAVs for photogrammetry

As a means of collecting 3D geometric data, UAVs are the most promising technologies among others. UAVs equipped with real-time kinematic (RTK) GPS receivers can create consistent 3D models at a relatively low cost (Daakir et al. 2015). For this reason, many researchers have studied the application of UAVs to construction sites. As the UAV industry grows, several novel data processing approaches have also been developed. Similar to TLS, direct and indirect geo-referencing approaches are used to project global coordinates to UAV-generated point clouds. Direct geo-referencing is suitable in environments where ground control points (GCPs) cannot be installed. For indirect geo-referencing, the location and position of the camera inside the UAVs is calculated using RTK-GPS and IMU (Yildiz and Oturanc 2014). Because of this, the accuracy of the point clouds generated by UAVs depends on the accuracy of the sensors installed in the UAVs. However, the vertical accuracy of the RTK-GPS is approximately ± 3 cm, which is above the grading tolerance for subgrade. Although a few studies have applied post-processed kinematic (PPK) GPS to improve accuracy (Stöcker et al. 2017), this method also failed to meet the accuracy required in the subgrade grading step. Unlike direct geo-referencing, indirect geo-referencing uses several GCPs on the ground to acquire the absolute coordinates of the point cloud. Since the positioning accuracy of indirect geo-referencing is higher than that of direct geo-referencing, several studies have adopted indirect geo-referencing for construction field surveys. However, the existing method cannot completely avoid the influence of GPS in UAVs because the GPS values are used in the structure from motion (SfM) stage to determine the exterior orientation (EO) of the camera. To eliminate the uncertainty of the sensors in UAVs, this study utilizes a novel method to calibrate the EO with specially designed ground targets.

3. Past case studies (Task 2)

In Task 2 of the research, the lessons learned from past GDOT construction projects were extensively studied. Through a nationwide online survey and interviews with the GDOT inspectors or project managers, the research team aimed to identify the following:

- Various survey methods used by contractors
- Past cases of measurement discrepancies
- Interoperability problems among different measurement methods

3.1 Survey issues on GDOT projects

The research team analyzed the previous issues on field survey for the road constructions in GDOT. Several types of surveying issues have occurred in Georgia over the past decades. Table 2 describes the summary of the survey measurement issues. As shown in Table 2, most causes of the survey errors are classified into three types as follows:

1. Long time gap between design and construction (changes in the surrounding environment)
2. Poor techniques in surveying (non-licensed surveyors)
3. Discontinuous survey (long interval of survey points)

The long-delay project may cause loss or damage of the reference points installed in design phases and poor communication between design engineers and contractors. The poor techniques in surveying are the results of the lack of licensed surveyors in contractors. Since construction contractors are not required to obtain a survey license, most construction surveys have been carried out by non-experts. The discontinuous survey is one of the serious reasons causing the survey errors. Since conventional measurement methods using total stations or levels measure only a few specified locations, it is difficult to have continuity between measurement points. Therefore, new surveying methods are needed to solve the discontinuity problem.

TABLE 2
Summary of the survey issues in GDOT

Projects	Issues	Actions
Widening project Calhoun, GA.	Error: 0.5’ vertical and 1.5’ horizontal	A mutually visible traverse between control pairs
	Too long-time gap	
Bridge replacement Jackson County, GA	Error: 100’ in the vertical elevation	Re-adjust the values using Geoid 12A
	Apply wrong Geoid for ortho. height	
New alignment Savannah, GA	Error: 0.25’ vertical and 0.2’ horizontal	Traverses were made between all control and level lines
	Too long interval of survey points	

3.2 Interview with contractors, surveyors, PMs, and owners

To discuss such issues on the field survey in road constructions, the research team interviewed contractors, project managers, surveyors, and owners in Georgia. Figure 2 depicts the summary of the interviews, and all interview reports are included in Appendix A. Although their opinions are different from each other, they agree that construction surveyors should be certified, and the pre-field survey should be conducted before earth-moving. Furthermore, they emphasized that unified and innovative survey methods are necessary, and the surveyor suggests laser scanning is the most efficient practice for grade control.

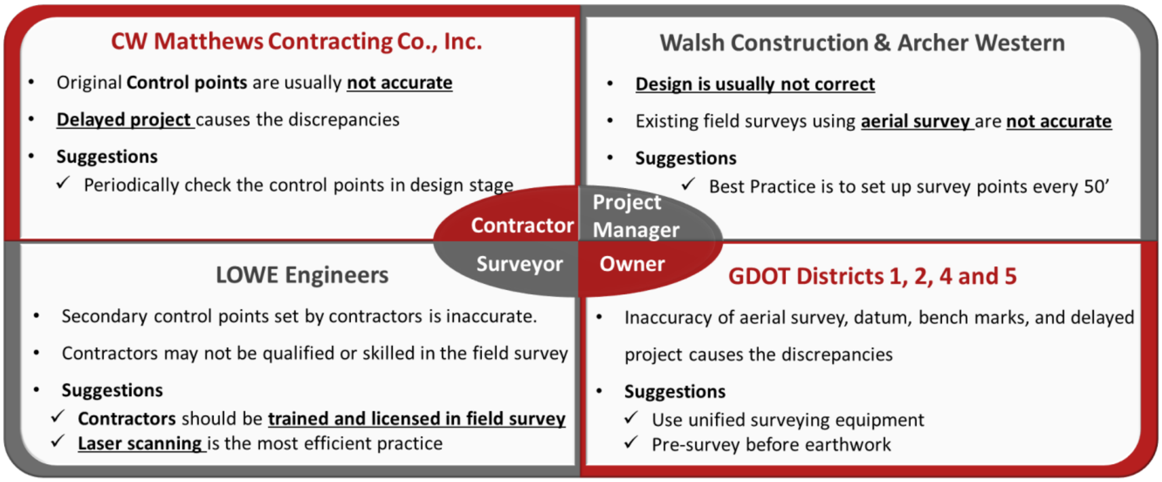


FIGURE 2
Summary of the interviews

3.3 Questionnaire survey

To obtain more diverse opinions for the survey issues, the research team conducted an online questionnaire survey on contractors, surveyors, designers/engineers, and owners across the country. Figure 3 describes the results of the survey analysis. A total of 109 responses were collected from the survey. In several questions, the answers between the contractors and the owners were quite different. For example, in ‘Q1. When were the discrepancies discovered?’ 50% of contractors said they found it before earthmoving, while owners said the discrepancies were found most often before grading. However, in ‘Q2. What caused the discrepancies?’ both contractors and owners answered that survey error in the design stage is the biggest reason for the discrepancies. Based on the results of the series of the past case studies, the team concludes that most discrepancies were found before earth moving or before grading, and most causes of the discrepancies were the survey errors in design or construction phases. As the result of the survey, therefore, the following recommendations were made:

1) check control points before earthwork,
2) inspect earthwork surface elevation before grading, and
3) use new field survey practices to reduce survey errors.

The details of the survey are included in Appendix B.

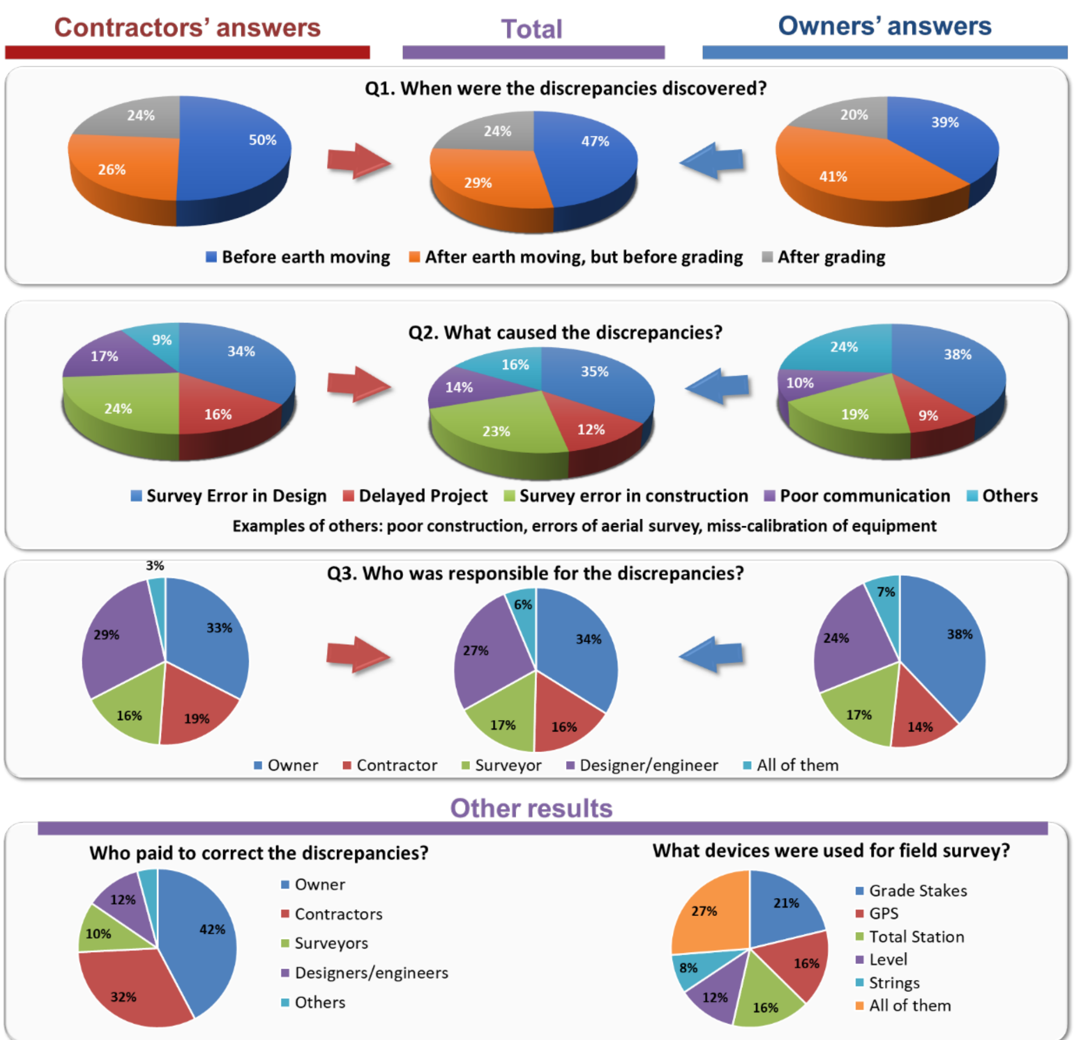


FIGURE 3
Summary of the questionnaire survey

4. Actual case study (Task 3)

In Task 3, several field case studies with GDOT's active road construction projects were conducted. The intent was to identify the causes of discrepancy measurements directly from active projects based on the knowledge obtained from the previous tasks. Through the actual case study, the research team assessed the performances of various technologies and data processing methodologies for collecting dense points of graded surfaces.

4.1 Test sites

The research team was assigned the South Calhoun Bypass project (GDOT PI#662510). The South Calhoun Bypass project was an ongoing highway construction project started from February 25, 2013, stretching from below the split on Ga. 53 east across U.S. 41 and I-75 and backing up to Ga. 53 on the east side of Calhoun Premium Outlets. The research team selected three field cases, STA 100-130, STA 200-230, and STA 410-435 where large-scale earthwork is performed as shown in Figure 4.

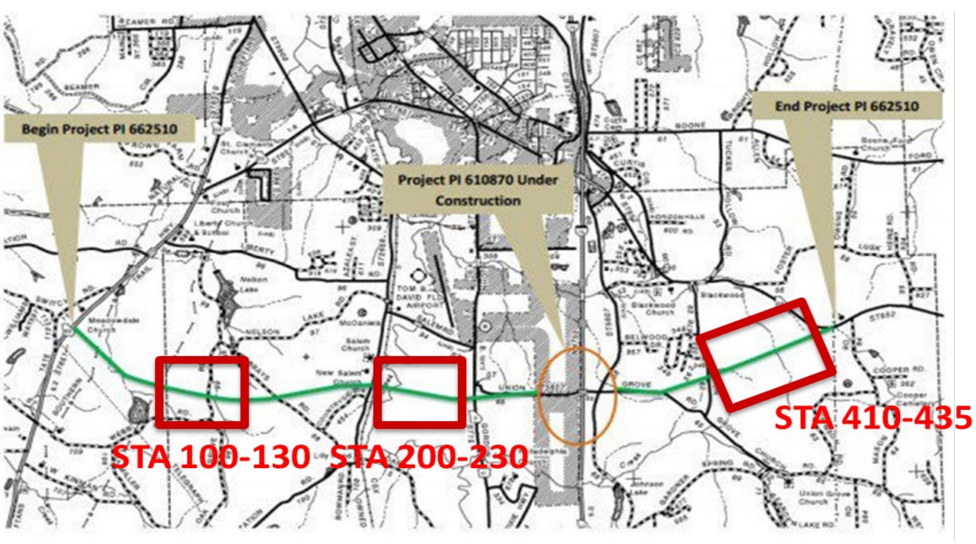


FIGURE 4
The field test sites in the South Calhoun Bypass project in Georgia

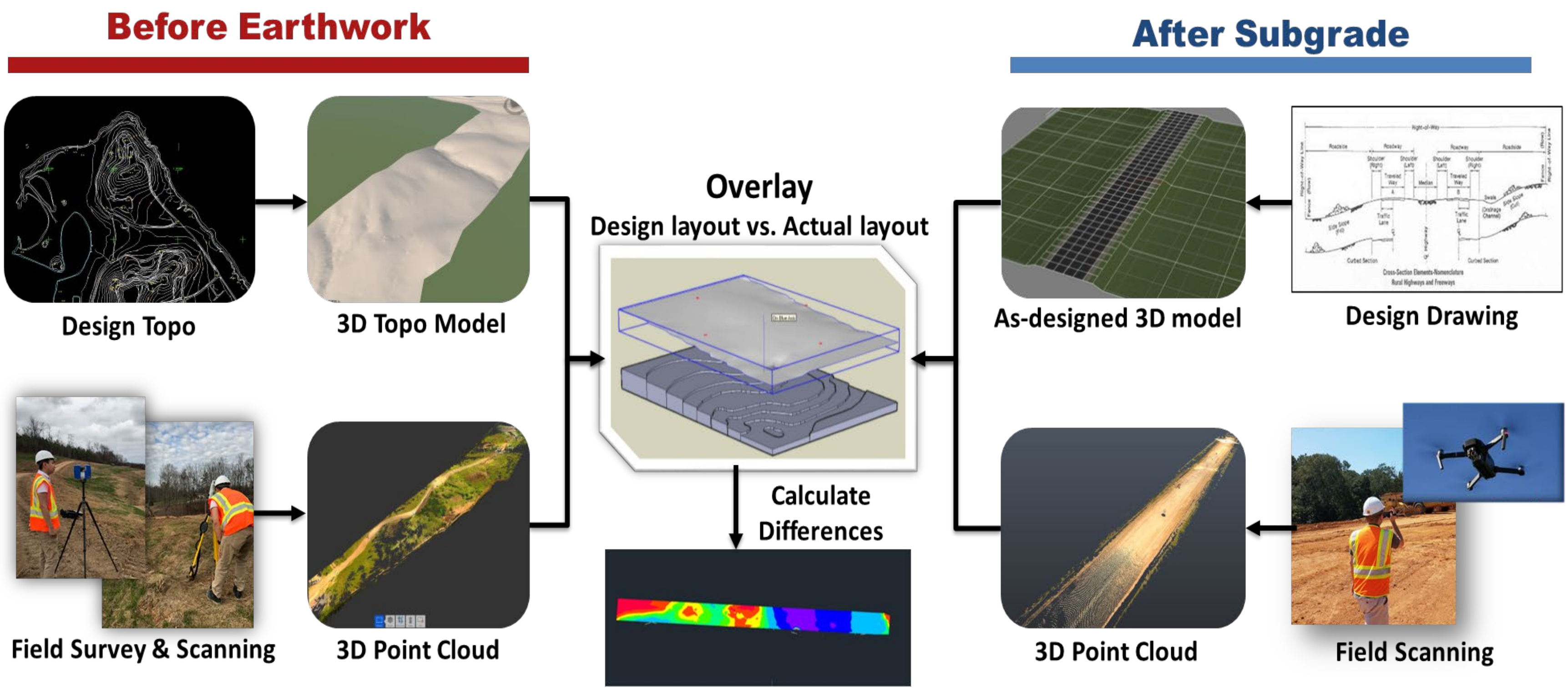


FIGURE 5
The overall framework for the field test

4.2 Methodology

4.2.1 Overall framework

Figure 5 presents the overall proposed framework of the field test. The research team conducted the field tests on two grading stages, before earthwork (cleared surfaces) and after subgrade grading (graded surfaces). The team collected geographic surface information and built as-is 3D models, and then the as-is 3D models were overlaid with as-designed models and finally the differences between the as-is model and as-built model were estimated and visualized. For this purpose, the team applied three data collecting tools and several data processing methods.

4.2.2 Data collecting tools

For the field geometric data collection, the team applied three types of field scanning technologies: terrestrial laser scanner (TLS), unmanned aerial vehicle (UAV), and mobile mapping system (MMS) as described in Table 3. The MMS was developed by the Robotics and Intelligent Construction and Automation Lab (RICAL) at Georgia Tech. The properties and specifications of the applied technologies are demonstrated in Table 4. To measure the performance of the three technologies, a robotic total station (RTS) was used as the ground truth because RTS has higher accuracy than the others.

TABLE 3
Test fields and applied technologies

		STA 200-230	STA 410-435	STA 100- 130
Cleared surface	Date	05/08/2017	01/04/2017	03/15/2018
	Technologies	TLS	TLS	TLS, UAV
Graded surface	Date	07/19/2018	10/07/2017	N/A
	Technologies	TLS, UAV, MMS	TLS	N/A

TABLE 4
The properties and specifications of the applied technologies

	Specifications	Properties
 TLS	- Ranging Error: ±2mm @ 10m - Camera resolution: 70 Mpix	- High resolution/accuracy - Relatively high labor force - Affected by ground conditions
 UAV	- Camera resolution: 12 Mpix - Max speed: 40 mph	- Relatively low accuracy - Low labor force - Affected by weather and location
 MMS	- Resolutions o Vertically: 0.16˚ o Horizontally: 0.1˚	- Moderate accuracy - High technique - Affected by ground conditions

4.2.3 Data processing methods

TLS with resection approach

In this study, a resection technique was used to calculate the scanner's orientation using three known points. For this purpose, the research team installed four sphere targets at each scan station and measured the sphere targets within each station, as depicted in Figure 6. Three of the four targets were used for resection, and the other was used as a check point (CP) for measuring the positioning accuracy. The interval between each scan was approximately 30 meters. The resolution of each scan was adjusted to a point spacing of 4 millimeters at a distance of 10 meters, and each scan took approximately 8 minutes. Finally, the positioning accuracy of this approach was compared to that of the indirect geo-referencing method. When using the indirect geo-referencing method, only one of the four targets at each scan station was used for geo-referencing, and the same CPs were used for the error assessment. The rest of the targets were used for the point cloud registration. Figure 6 is the TLS and sphere targets used in this test.

FIGURE 6
Laser scanning with sphere targets for resection

UAV using AprilTags

A dense point cloud is created from the UAV's photo images through Structure from Motion (SfM) process, which is a photogrammetric technique for estimating the depth of structures from 2D image sequences. Since the SfM reconstructs the 3D structure of a scene from 2D images, the dense point cloud does not have absolute scale and coordinates. Therefore, to project global coordinates to the point cloud generated from SfM, additional geo-referencing processes are required. To improve the photogrammetry process, this study proposed a novel geo-referencing approach that uses AprilTags for UAVs developed by The APRIL Robotics Laboratory University of Michigan (Olson 2011). As a visual fiducial system, AprilTags can be used to calibrate the exterior orientation (EO) parameters of the camera. Moreover, since all AprilTags have different shapes, the algorithm can detect each tag in every image. Based on the measured tag position (x_T , y_T , z_T) and rotation (θ_T) in camera coordinates, it is possible to obtain the UAV position in global coordinates (x_g, y_g, z_g) as shown in (1) and (2):

$$\Delta\theta = \theta_C - \theta_T \tag{1}$$

$$\begin{bmatrix} x_g \\ y_g \\ z_g \end{bmatrix} = \begin{bmatrix} x_C + \cos(\Delta\theta)\ x_T - \sin(\Delta\theta)\, y_T \\ y_C + \sin(\Delta\theta)\ x_T + \cos(\Delta\theta)\, y_T \\ z_C + z_T \end{bmatrix} \tag{2}$$

where, θ_C is the rotation parameter of camera and the coordination of the camera is (x_C, y_C, z_C). To obtain the absolute coordinates and rotation parameters of the images from the tags, three vertices of each tag placed on the ground were measured. The tags were installed at the interval of 30 meters to ensure that at least one tag is visible in every image. A total of 10 AprilTags were used for geo-referencing, and eight CPs were installed on the ground to measure the positioning error. For this purpose, this study also used a quadcopter drone equipped with a camera with a resolution of 3,000 × 4,000 pixels. To fix the ground sample distance (GSD) to one centimeter, the flight height was set to 30 meters above ground level. The overlap ratio was 90%, and the total flight time was approximately 7 minutes. Figure 7 shows the UAV and AprilTags that were employed in this test. Finally, the results derived from this approach were compared to the results of a conventional indirect geo-referencing method using GCPs.

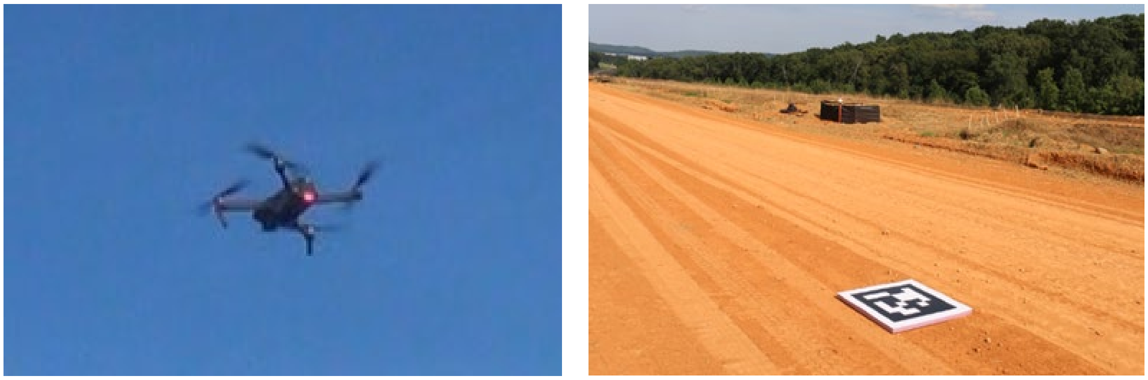


FIGURE 7
The UAV (left) and AprilTags (right) used in this study

Mobile laser scanning robot

An all-terrain mobile robot called the Ground Robot for Mapping Infrastructure (GRoMI) was used as an MMS in the field test. GRoMI is an unmanned ground vehicle designed for 3D laser mapping with simultaneous localization and mapping (SLAM) technology (Kim et al. 2018). The GRoMI is composed of two major parts: a laser scanning system and an autonomous mobile robot platform. The upper laser scanning part, which collects 3D mapping information, consists of five 2D laser scanners and a built-in digital camera. The lower mobile robot component, which collects localization data, has four wheels with encoders, object avoidance sensors, an inertial measurement unit (IMU), and a navigation camera. The characteristics of this system are that 1) data acquisition is possible while the robot is moving, 2) red-green-blue (RGB)-mapped high-resolution point clouds can be obtained using a digital single-lens reflex (DSLR) camera, and 3) robot navigation and data collection can be carried out remotely or autonomously. The resolution of each line laser used in this test was 0.16 degrees in the vertical direction and 0.1 degrees in the horizontal direction. The digital camera captures 8 pictures per 360º scan to obtain the RGB information of the construction site.

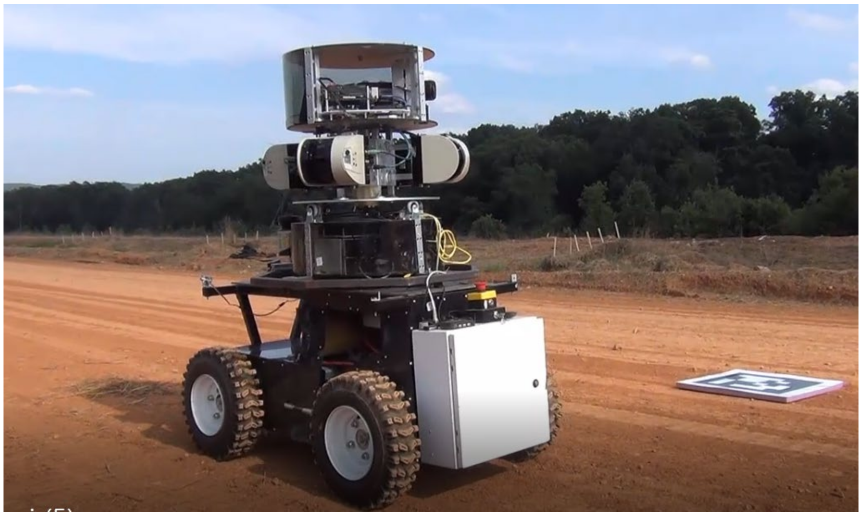


FIGURE 8
GRoMI used in this study

4.3 Test results

4.3.1 Error assessment

Before applying the previously introduced technologies to 3D grade control in road construction sites, the research team assessed their positioning accuracy to confirm if the accuracy satisfies the required grade tolerances. The technologies and data processing methods for the error assessment are demonstrated in Table 5. For the geo-referencing, the research team set up several types of ground targets and measured them with a total station. The measured targets were used as both ground control points (GCPs) for geo-referencing and check points (CPs) for accuracy analysis. The AprilTags remained in the same locations for the UAV. Figure 9 depicts the location of the GCPs, CPs, and scanners. In this study, 13 GCPs and 5 CPs were installed around the site.

TABLE 5
The data collecting tools and processing methods used in the error assessment

Test sets	Tools	Geo-referencing	Point cloud generation
Set 1	TLS	Indirect geo-referencing	Target-based registration
Set 2		Resection	Resection-based registration
Set 3	UAV	Indirect geo-referencing	SfM
Set 4		Exterior orientation (EO) parameter calibration with AprilTags	SfM
Set 5	MMS	Resection	Resection-based registration

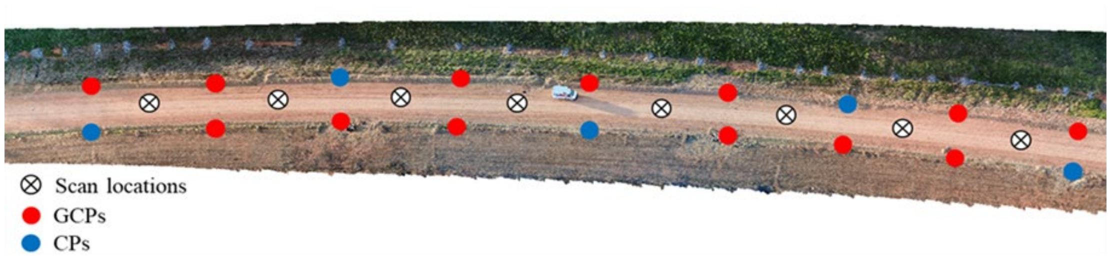


FIGURE 9
The locations of GCPs, CPs, and scanners

Figure 10 shows the point clouds created by TLS (a), UAV (b), and MMS (c). Since TLS and MMS are ground-based laser scanning tools, there were some occluded areas at the uneven surfaces. In contrast, the UAV-generated point cloud was finely created with few occlusions. However, the positioning accuracy of the UAV-generated point cloud was relatively low compared to the point cloud generated by the ground-based laser scanners.

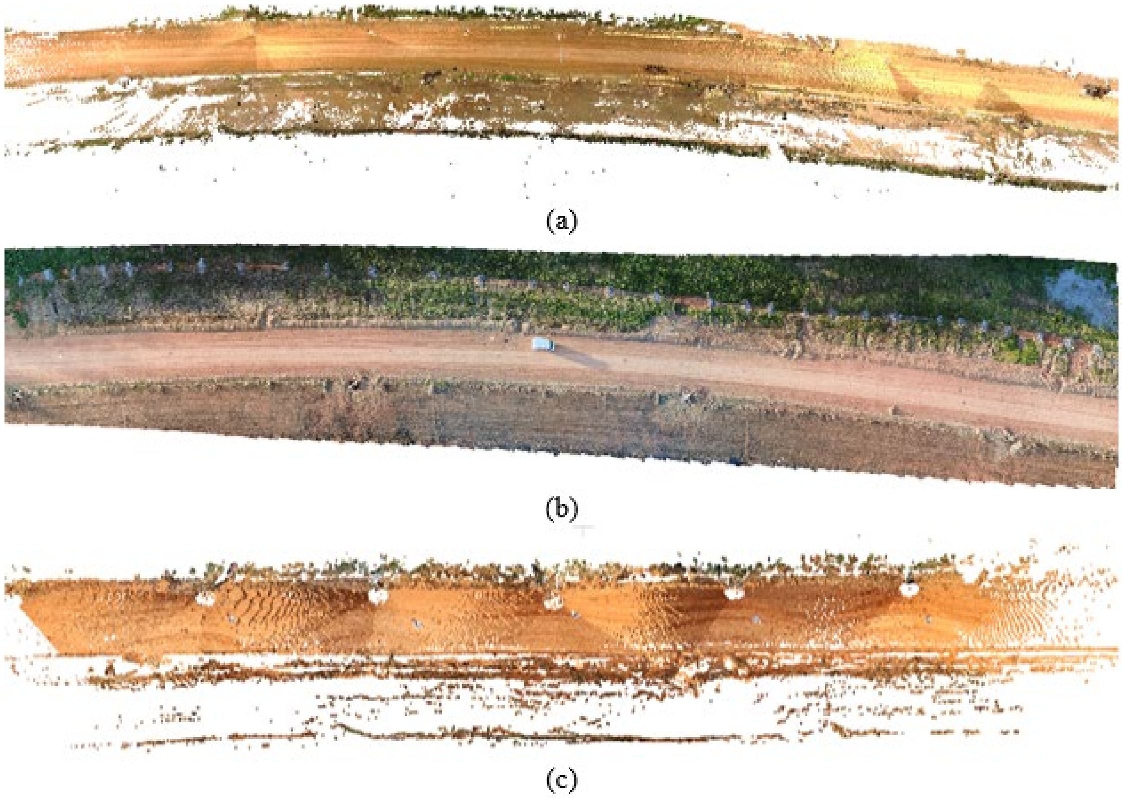


FIGURE 10
The point clouds created by TLS (a), UAV (b), and MMS (c)

Table 6 presents the results of the error assessment for the point clouds created by different instruments and data processing methods. The overall time includes the preparation, operation, measurements, and processing time. Compared to TLS, UAV and MMS are time-efficient instruments but are not suitable for subgrade's grade control in road construction because the positioning errors of the point clouds generated by UAV and a mobile robot do not meet the required tolerance for subgrade grading (0.5 in.). For TLS measurements, the resection-based point cloud registration method is time-consuming because it requires more targets than other methods. Since the resection-based registration method does not have the accumulative error that occurs when registering consecutive point clouds in the longitudinal direction, however, it could significantly improve the positioning accuracy.

TABLE 6
The results of the error assessment

Instruments	Data processing methods	Root mean square error (RMSE) in ΔH (in.)	Overall time (min)
TLS	Target-based registration	1.220	184
	Resection	0.551	194
UAV	Indirect geo-referencing	1.967	108
	Resection with AprilTags	1.457	194
Mobile laser scanning robot	Resection	1.750	170

4.3.2 3D grade control

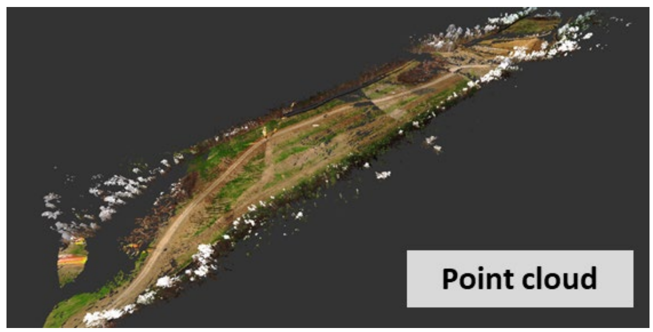
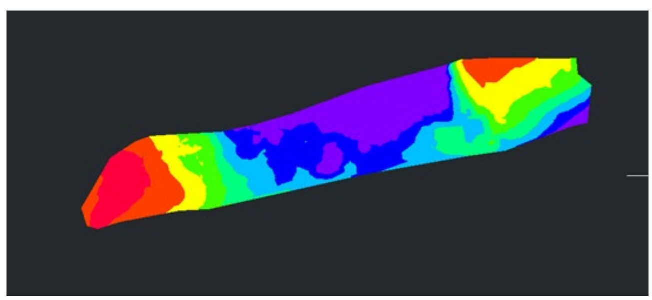
Cleared field (STA 410 – 435)

The research team collected dense points of cleared surfaces from STA 410 to STA 435 with TLS. For the target-based point cloud registration and geo-referencing, the team installed permanent stakes around the field. Total distance for the laser scanning was approximately 2,500 ft. (762 m) and total time spent was 24.5 hours, which includes the times for stakes installation, target measurement, and laser scanning. Figure 11 is the scene of the laser scanning and the field survey, and Figure 12 shows the target installation process. Table 7 summarizes the visualized results on the cleared site. The results of modeling and visualization for other cleared sites (STA 200 – 230 and STA 100 – 130) are shown in Appendix C.

FIGURE 11
The scene of the laser scanning (left) and field surveying (right)

FIGURE 12
Target installation process

TABLE 7
The results of visualization and calculation of the inaccuracies for a cleared surface

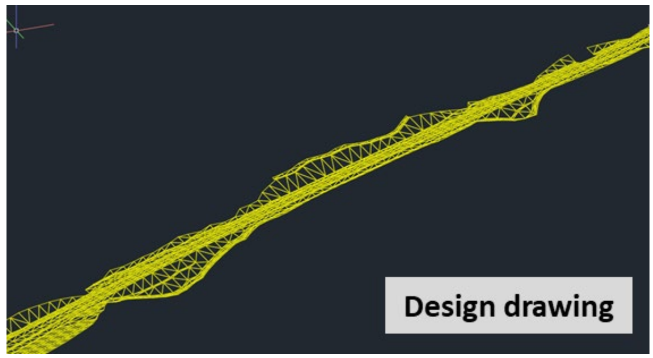
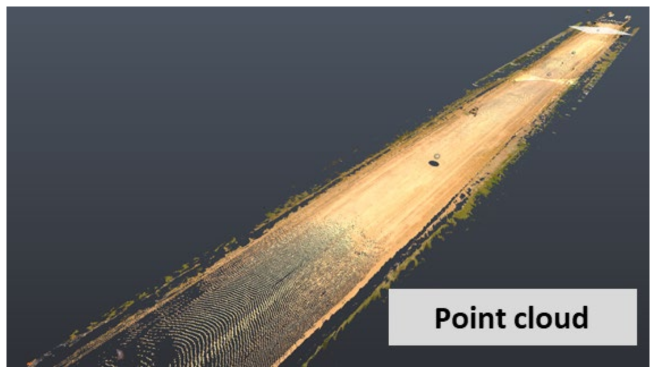
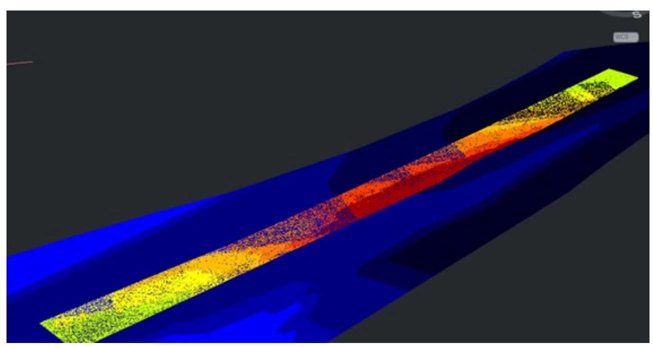
<table>
<tr><th colspan="2">STA 410 – 435 (Cleared surface)</th></tr>
<tr><td>As-designed topo model</td><td>
</td></tr>
<tr><td>As-built point cloud</td><td>
</td></tr>
<tr><td>Elevation differences</td><td></td></tr>
<tr><td>Discrepancy details</td><td>- Max.: 32.68’
- Min.:-33.83’
- Average: 1.24’
- Volumes
○ Cut: 54,765 Cu. Yd.
○ Fill: 73,114 Cu. Yd.
○ Net: 18,350 Cu. Yd.</td></tr>
</table>

Graded field (STA 410 – 435)

The research team also obtained dense points of graded surfaces from STA 410 to STA 435 with TLS. In this test, three sphere targets and one checkerboard target for each scan were used for point cloud registration and geo-referencing. For this purpose, the sphere targets were placed between each scan position, and the checkerboard target were attached to vertical objects on both sides of the road as shown in Figure 13. Total distance for the laser scanning was approximately 1,600 ft. (490 m) and the total time spent was 10.6 hours, which includes the times for target installation and measurement, and laser scanning. The laser scanning interval was 30 m. Table 8 summarizes the visualized results on the graded site. The results of modeling and visualization for other graded sites (STA 200 – 230) are shown in Appendix C. Since STA 100 – 130 section was not graded until the end of this research, the research team could not measure the graded field of STA 100 – 130.

FIGURE 13
The sphere targets (left) and checkerboard target (right) used in this test

TABLE 8
The results of visualization and calculation of the inaccuracies for a graded surface

STA 410 – 435 (Graded surface)	
As-designed topo model	
As-built point cloud	
Elevation differences	
Discrepancy details	- Max.: 0.852’ - Min.: -0.043’ - Average: 0.459’ - Volumes (42.601 Sq. Ft.) ○ Cut: 0.01 Cu. Yd. ○ Fill: 22.00 Cu. Yd. ○ Net: 21.99 Cu. Yd.

5. Development of the best practice guidelines

Based on the findings from the lessons learned and field case studies in the previous tasks, the research team has identified possible alternatives for 3D grade control as shown in Table 9. To identify the optimal instrument and data processing method, the team considered the accuracy, time, and labor cost. The team identified that if the positioning error is lower than the tolerance of the discrepancies between designated grade level and actual grade level, its accuracy is acceptable. The team also measured the overall time including preparation, measurement, and generation of a 3D point cloud model for 3,000 feet length of a road construction site. The labor cost was determined based on the amount of manpower required in the field tests.

Since the positioning accuracy of all alternatives met the required accuracy for cleared surface (6 in.), all three tested technologies are acceptable alternatives for the cleared site survey. However, the ground condition of the cleared surfaces is uneven and covered with brushes, which causes many occlusions for ground-based laser scanning. That being said, UAV can be more appropriate for the 3D grade control for the cleared surface. For the graded surface, only TLS using resection-based registration method satisfied the tolerance for grading subgrade (0.5 in.). Also, RTS for the grade control of paved surfaces is recommended since RTS is the only alternative that can meet the required tolerance for the paved surface (0.25 in).

TABLE 9
The best technologies for the 3D grade control at each grade stage

Field	Tolerance	Tools	Data processing methods	Accuracy* (error < tolerance)	Time cost	Required labor force
Cleared surface	6 in. (Digital terrain model)	TLS	Indirect geo-referencing	O	Intermediate	Intermediate
			Resection	O	High	High
		UAV	Indirect geo-referencing	O	Low	Low
			AprilTag	O	Intermediate	Intermediate
		MMS	SLAM based registration	O	Low	Intermediate
			Resection	O	Intermediate	High
Graded surface	0.5 in. (Subgrade)	TLS	Indirect geo-referencing	X	Intermediate	Intermediate
			Resection	O	High	High
		UAV	Indirect geo-referencing	X	Low	Low
			AprilTag	X	Intermediate	Intermediate
		MMS	SLAM based registration	X	Low	Intermediate
			Resection	X	Intermediate	Low
Final paved surface	0.25 in.	RTS	Robotic measuring system	O	Low	Low

* where, (O) means the error is smaller than tolerance, and (X) means the error is larger than tolerance

Through the actual case study, the research team also provided the following recommendations for the implementation of each technology for 3D grade control:

1. TLS
    a. Scanning interval: not more than 30 m (for enough overlap)
    b. Point resolution: less than 1cm at 10 m
    c. Subsampling after registration → File size: less than 100MB/km for efficient data processing
2. UAV
    a. Overlapping ratio: more than 80%
    b. Flight height: less than 50 m → GSD: smaller than 2cm
3. File formats for better interoperability
    a. Point cloud: .ply or .txt
    b. 3D surface model: LandXML or TIN

6. Conclusions

Through the series of the tasks, this study provided the best practices for 3D grade control in road construction projects. First, the research team conducted several past case studies to identify the causes of the discrepancies between the as-designed model and as-constructed model in road grade construction. As a result, the causes of the differences are 1) long time gap between design and construction phases, 2) poor techniques in surveying, and 3) long interval between survey points and references. To mitigate the elevation errors in road grade construction, the research team recommends to 1) check control points before earthwork, 2) inspect earthwork surface elevation before grading, and 3) adopt new field survey tools that collect dense points from the surfaces.

In addition, the research team conducted field tests at actual highway construction sites in Georgia to assess the accuracy of advanced technologies collecting dense points from the surfaces. For this purpose, three instruments, TLS, UAV, and MMS, and several data processing methods were tested. The results of the field test indicate that TLS using a resection-based registration method was the best practice for the subgrade grade control because only this approach could satisfy the accuracy required for the subgrade grade control. UAV and MMS are the most time-effective technologies for generating a 3D surface model of the cleared sites and the accuracies are satisfied with the tolerance for the cleared site survey.

Consequently, this research recommends to 1) carry out mandatory field surveys before earth moving, 2) generate a 3D surface model from a dense point cloud, 3) adopt UAV or MMS for the site clearing stage, 4) adopt TLS for the subgrade grading stage, and 5) use RTS for the final surface paving stage. By providing the best practices guidelines for grade control and referencing, GDOT may experience financial benefits by resolving the issues of decreased material overruns and project time extensions due to grade control inaccuracies.

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APPENDIX A: REPORTS OF INTERVIEW IN GEORGIA

- GDOT District 1

Date	January 23, 2017
Time	3:30 pm
Location	GDOT District 1, 2505 Athens Hwy, Gainesville, GA 30507
Company	GDOT District 1
Contents	The major causes of the inaccuracy in grade elevation were the inaccuracy in the surveying data. The surveying was done on a triangular terrain. Crests, existing drains, and cracks were possibly missed during the surveying. GPS was used on construction sites by the contractor for surveying, which had a low accuracy. One of the suggested solutions to improve this problem is the use of symmetrical terrain instead of triangular terrain during the design phase of the project. The accuracy would also be improved if the actual survey was conducted instead of using GPS; however, using GPS is cheaper and less time-consuming. The existing elevation data were not up to date, which also contributed to the error. The procedures of site inspection are multiple compaction tests, asphalt, concrete, solid packs, and steel test. Laser scanners can be used in the field if the initial data were accurate. However, the data were normally too old. The data could also be used to determine the amount of the right of way. If a wall is needed to be built in the field, or more work is done on the slope, the inaccuracy of the surveying data would affect more. This means the data must be collected relatively accurate, and under 5-year old under these circumstances. To design an effective plan, once the concept of the project is developed well in multiple stages; the conceptual design starts, followed by any environmental approval and drainage situation. After the final review, the design will be issued for construction. The engineer in GDOT District 1 also discussed that it was normal to find mistakes in plans, in field, and after the design was finished. Reviews are conducted along the plan being created. Another review will be conducted in the field when the plan is 90% to 99% finished. The review is majorly focused on the grade control and elevation issues. If issues were found, the review report would be sent to the designers for them to decide if major changes in the plan are needed. GDOT will take responsibilities in the extra cost of time and money.

- GDOT District 2

Date	March 7, 2017
Time	1:00 pm
Location	GDOT District 2, 643 Hwy 15 S, Tennille, GA 31089
Company	GDOT District 2
Contents	Engineers in GDOT District 2 pointed out that such situation that the plan is not consistent with the actual site condition rarely happens in District 2. They also mentioned that there were only two projects with such grading discrepancy they have experienced in the past. The contractors claimed to discover grading discrepancy at the site before the construction, but GDOT sent their own surveyors and construction engineers and decided the discrepancy was negligible. Even though this situation has been well handled and hardly found, discrepancies have happened throughout the time. The main factor that could cause such discrepancy was that contractors sometimes do not use the control package provided by GDOT properly. The engineers in GDOT District 2 also stated that contractors are responsible for catching and reporting such discrepancies before the construction starts, and are required to verify the cross section with the plan. During the excavation period, contractors are paid to remove a certain amount of soil to fulfill the Cut part in a Cut and Fill design. An estimation will be made with the grading as a lump sum regarding the volume of soil in the cubic yard in the contract. However, if there happens to be any discrepancies or changes in the site than the grading plan, GDOT will negotiate with the contractors about the lump sum and settle on a new payment. Contractors, who fail to identify and inform GDOT the differences, shall take great responsibilities in the process.

- CW Matthews (Contractors)

Date	November 29, 2016
Time	12:00 pm
Location	CW Matthews Office, 1672 Old Highway 41, Marietta, GA
Company	CW Matthews
Contents	CW Matthews (CWM) explained that often it is found from the differential leveling process that the original control points are not accurate. An example project, Abbott's Bridge, the control points elevation was off by a total of 4". At this point, CWM can send their data back to GDOT for redesign or revision. CWM stated that the plans that GDOT sends often include just two control points, which is not enough data for CWM to accurately construct or verify. One of CWM's surveyors is a professionally certified land surveyor in the state of North Carolina, but currently, Georgia does not require construction surveyors to be certified. Some other technologies that CWM is currently utilizing include photogrammetry and GPS equipment. However, the accuracy does not satisfy the required accuracy for the road grade control. Once CWM develops all of their own 3D models, they can send the survey data to GDOT via .txt or .csv file format. Regardless of the surveying method, all data can be sent via this file format. CWM stated that 95% of programs will accept a .dwg file or .dtm file. After beginning construction, if it is realized that the grade ends up being incorrect, CWM typically has the freedom to just revise it with GDOT approval, unless it is a serious discrepancy. GDOT has to approve any revised profile. Suggestions: • GDOT should periodically spot-check their control points as their design progresses. • GDOT uses Microstation as their platform while CWM uses Terramodel, which are not always compatible. • The design drawings do not include enough information. The goal of the designer is only to get the plans put together for approval.

- LOWE ENGINEERS (Surveyors)

<table>
<tr><td>Date</td><td>November 7, 2016</td></tr>
<tr><td>Time</td><td>12:00 pm</td></tr>
<tr><td>Location</td><td>CW Matthews Office, 1672 Old Highway 41, Marietta, GA</td></tr>
<tr><td>Company</td><td>LOWE ENGINEERS</td></tr>
<tr><td>Contents</td><td>The Georgia Department of Transportation (GDOT) has very strict standards regarding the practices of surveying. All surveying data are to be based on the State Plane Coordinate System, as required by GDOT.

There are a number of different methods that can be used for surveying such as laser scanning, robotic total station, and photogrammetry. It was advised that laser scanning proves to be the most accurate method and would be the quickest way to check the as-built conditions versus the design.

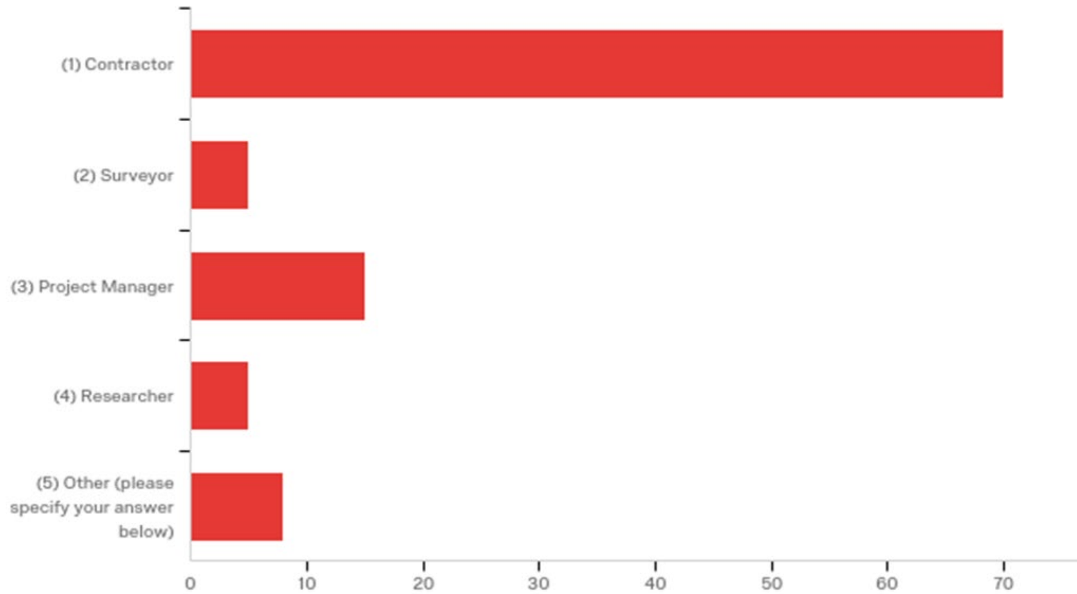
Some of the problems with laser scanners are that they are very expensive to purchase and constantly require maintenance and updates. To LOWE ENGINEER's knowledge, GDOT currently does not own a laser scanner because of the costs. Another problem with laser scanning is that LIDAR surveying and photogrammetry are both inaccurate at this time and are not transparent with the ground data. Because of this, all LIDAR and surveying data must be ground checked according to GDOT standards.

GDOT has very specific standards on how the professional land surveyor develops these control points. The contractor responsible for construction can then pull its own controls, but it is imperative that it follows the same standards as the professional land surveyor. Both GDOT and the contractors have dedicated QA/QC staff, but neither entity has a professional land surveyor that they use to check the control points that they develop.

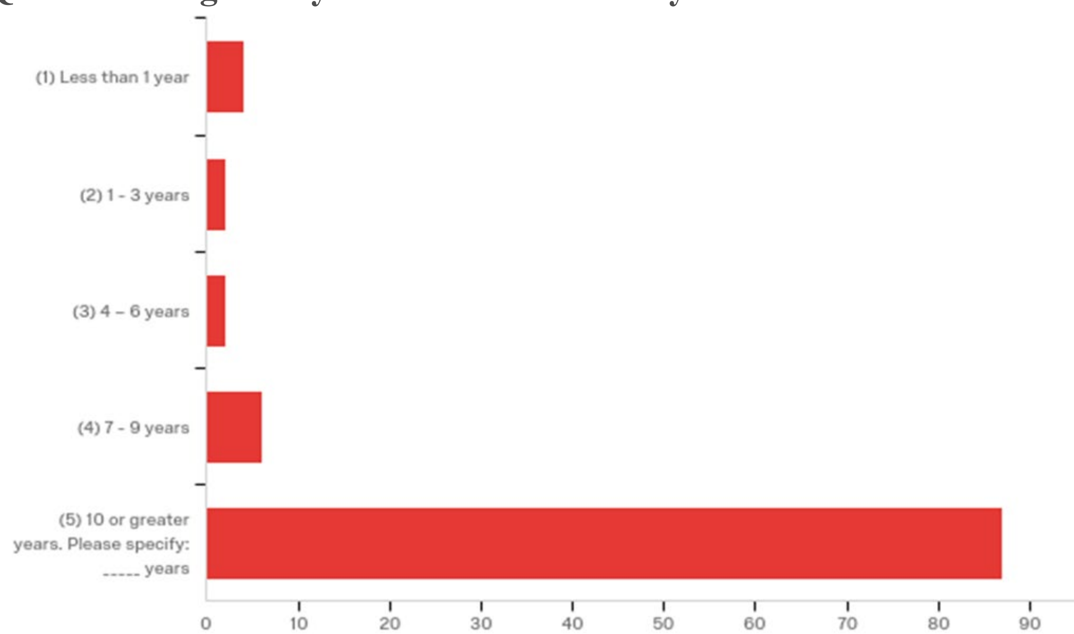
Suggestions :
• The control points are ensured throughout all construction processes.
• Surveyors in both GDOT and contractors are needed to be trained.
• Laser scanning would be the best practice for the construction survey.</td></tr>
</table>

APPENDIX B: SURVEY REPORT

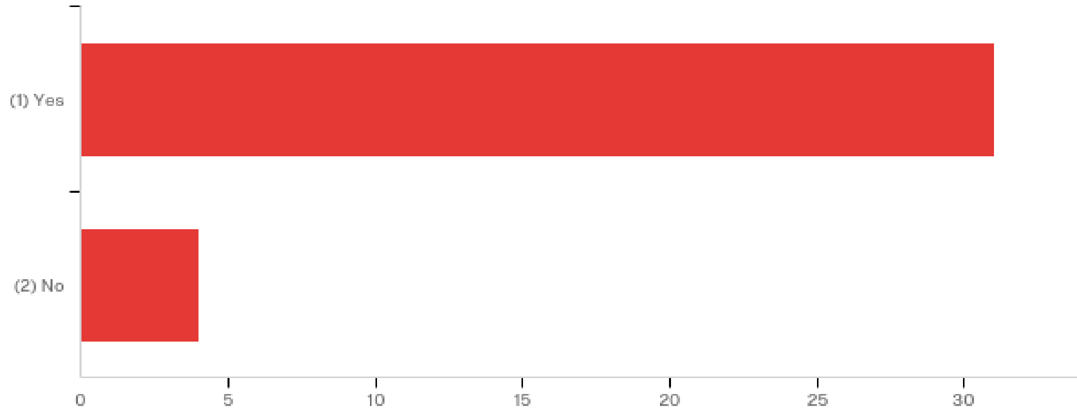
Q1 - In what category do you belong to?



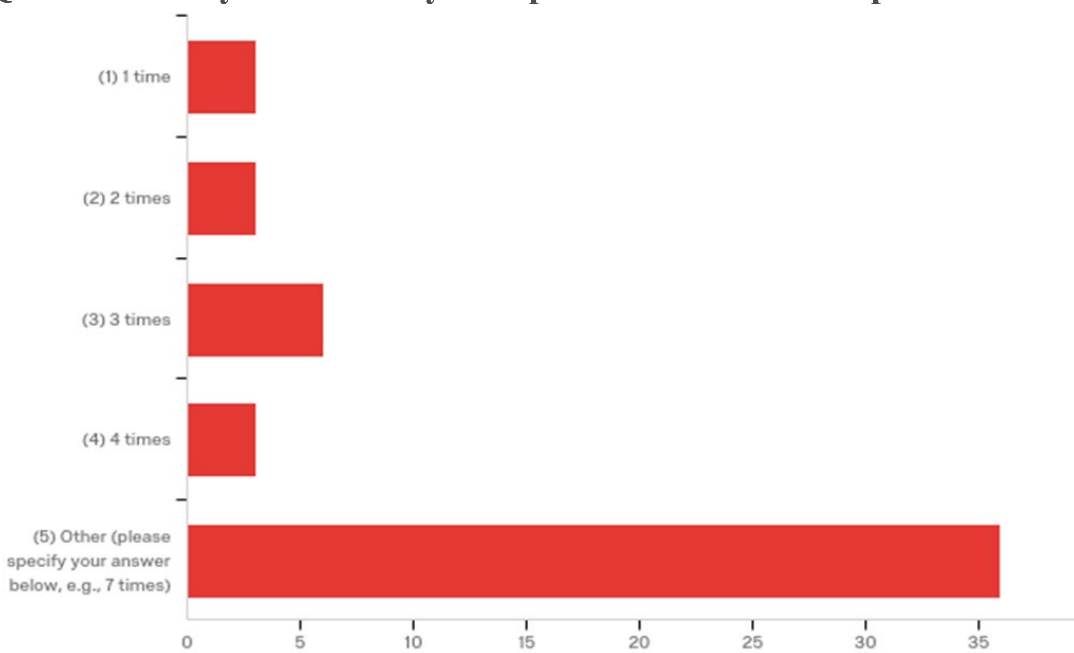
Q2 - How long have you worked in roadway construction field?



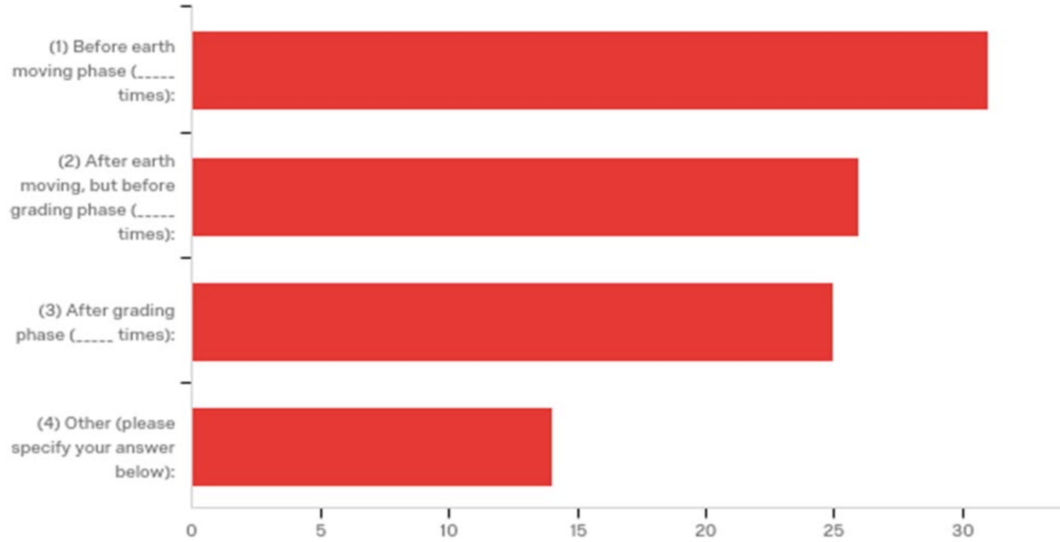
Q3 - Have you ever experienced significant discrepancies between design layouts and actual layouts that caused additional works and loss in cost?



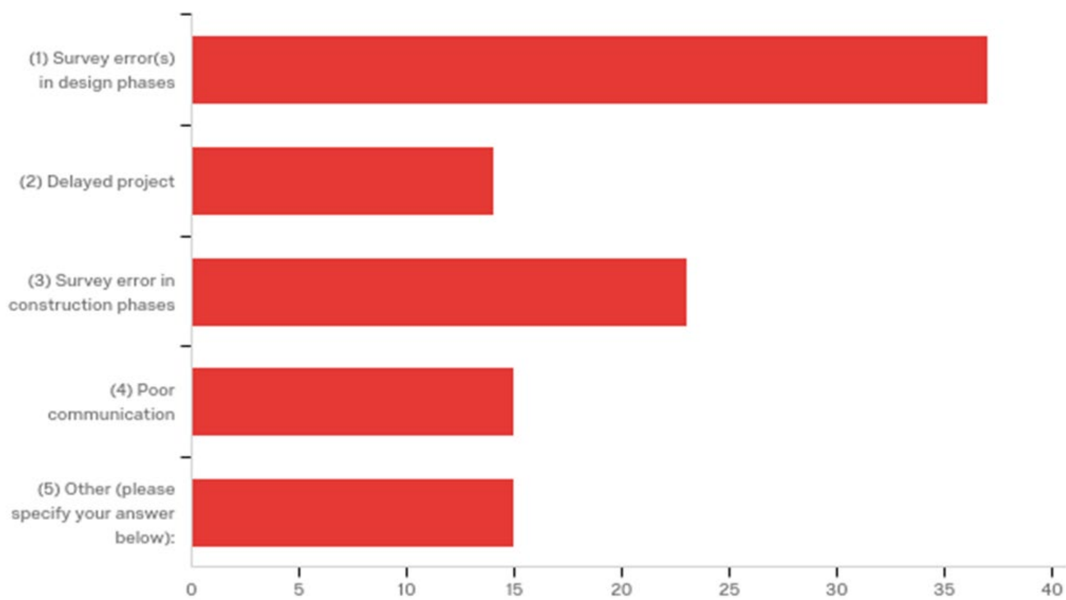
Q4 - How many times have you experienced such discrepancies?



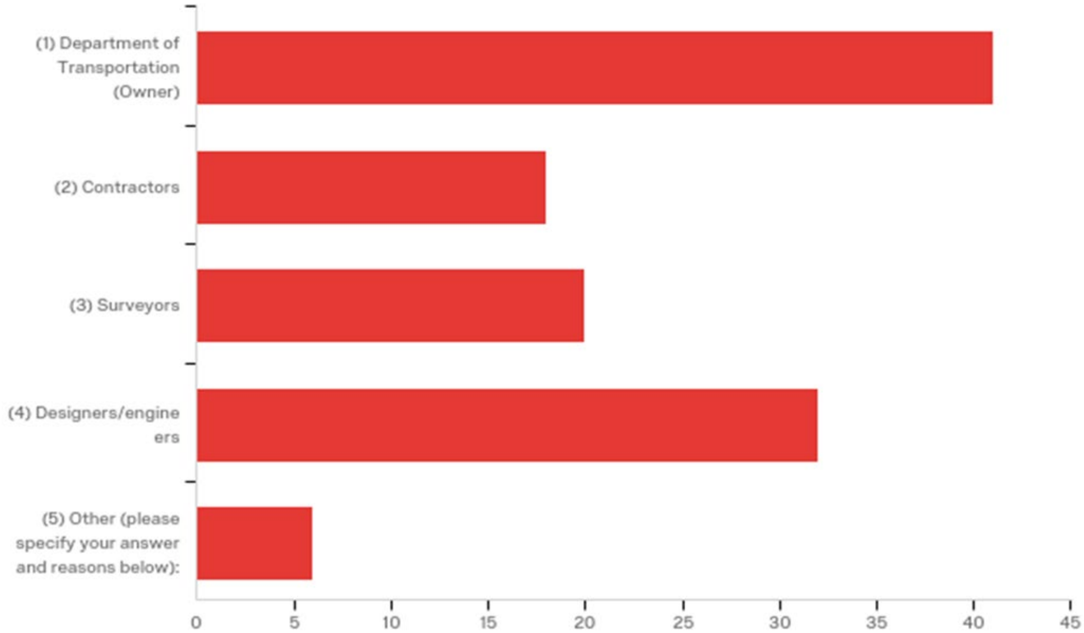
Q5 - When did you discover discrepancies? Select all the items as they apply to you.



Q6 - What caused the discrepancies? Select all the items as they apply to you.



Q7 - Who was or would be responsible for the discrepancies? Select all the items as they apply to you.



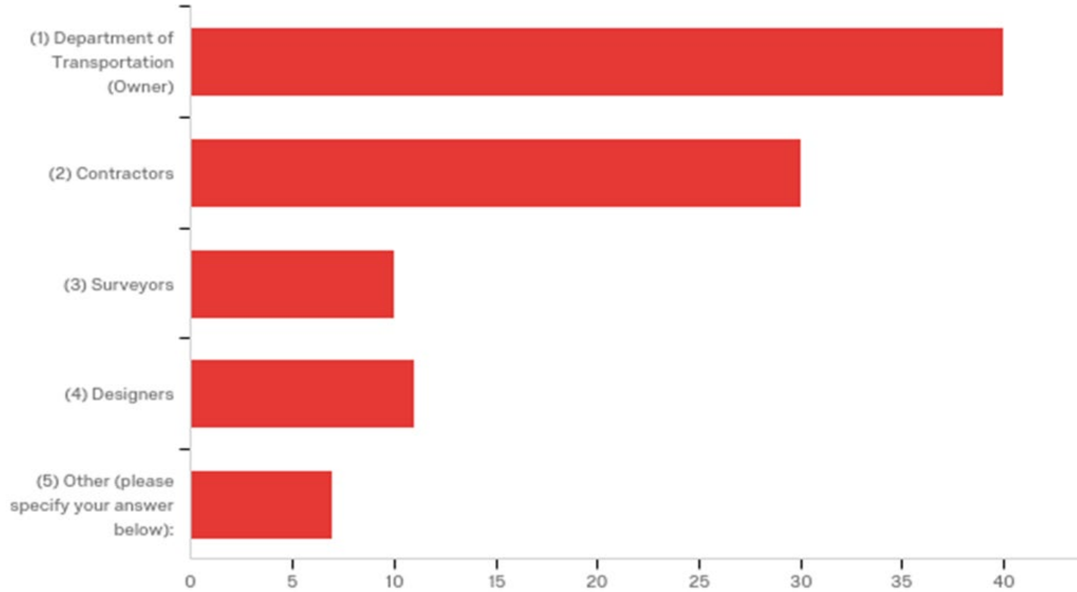
Q8 - How long did it take to correct the discrepancies?

- Varies on discrepancies.
- Mostly resolved in the field.
- Varies.
- Hour to months.
- Anywhere from a few weeks to many months depending on the scope of work and size of the project.
- 2 months for issues that do not involve environmentally sensitive areas, 6 months for issues that do involve environmentally sensitive areas and require a permit modification.
- Finding that existing ground is different than what shows on the plan requires weeks to correct. For example, a 6-mile road with existing ground incorrect would take about 3 weeks to correct. If the existing ground is different than what is shown in the plan and depending on where it is different would possibly require stones, walls, concrete structures, and bridges to be re-designed.
- A few days to a few months.
- Varied from 2 months to 7 months.
- It varies depending upon the discrepancy, anywhere from a few hours to many days.
- Days.
- Typically one week or less.
- 1 week.
- Depending on severity 3 - 5 work days.
- Some issues would take weeks, 14" of extra base asphalt to build up an existing roadway that was just supposed to be 4" overlay. That is one example, sewer pipe inverts that had to be recast to match correct inverts.
- 1 day-1 month.

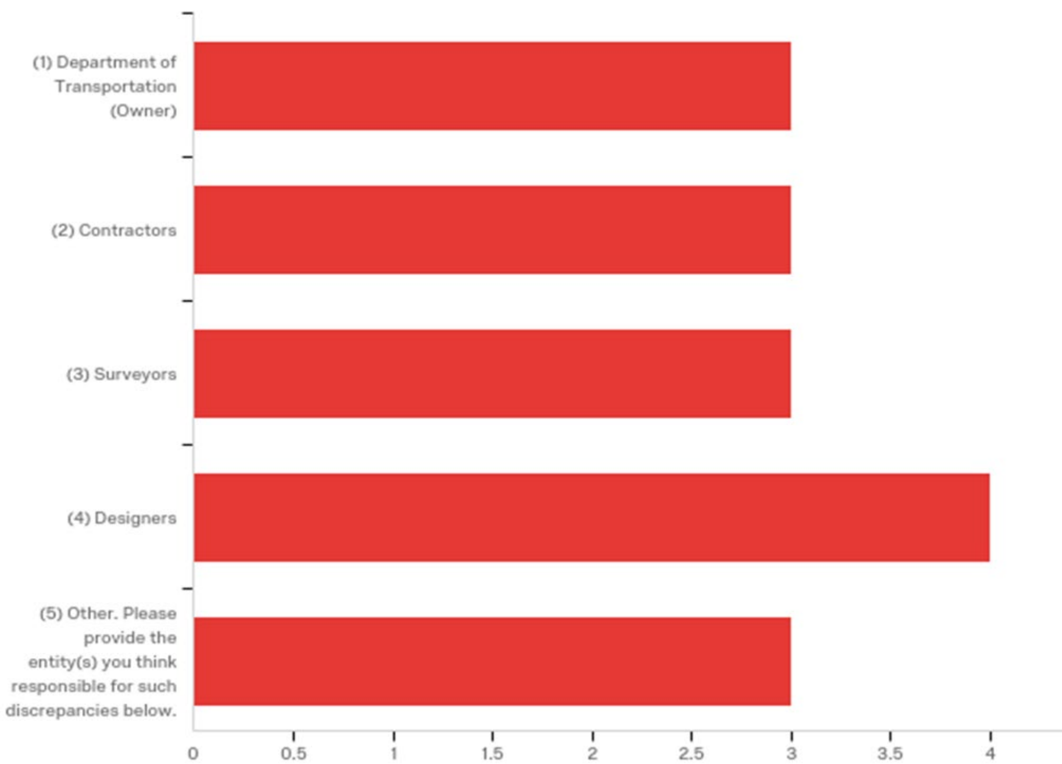
Q9 - How much did it cost to correct the discrepancies?

- Varies on discrepancies.
- The main issue was time. Time to report issue, time for DOT to review, time for DOT to make a decision, time to re-design, time to rebuild.
- Every issue is different.
- A little to $100,000 plus.
- Anywhere from a few thousand dollars to a few hundred thousand dollars.
- Generally, these are related to embankment tie-ins near the project limits. Adding Walls is very expensive. Increasing the height of a wall that was already in the plans is less expensive. Stream Migration or wetland delineation can affect permitting which increases the cost of mitigation credits.
- We have found that when existing conditions are not located properly it can cost several thousand dollars to correct. In extreme cases, an error was found in a 2012 project that cost the DOT millions of dollars to correct the issues and extended the contract by several years.
- $200,000 to $7,000,000.
- I don't know.
- Not sure.
- This can vary quite a bit from a few thousand to much more.
- $5,000.
- Costs were not tracked.
- Calculate 14" of asphalt base @ $200/ton over a three-lane roadway for one mile.
- $1,000-$1,000,000.

Q10 - Who paid the cost due to the discrepancies? Select all the items as they apply to you.



Q11 - If any discrepancy happened in a road grading phase, who do you think would attribute the discrepancies and why? Select all the items as they apply to you.

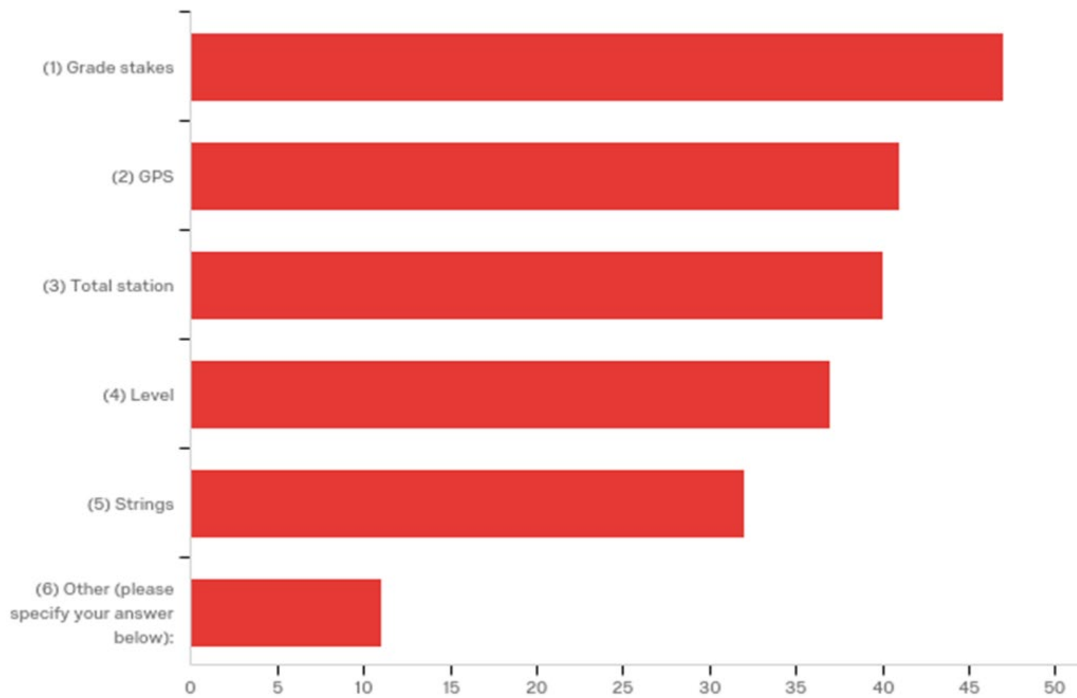


Q12 - What would be the best ways of reducing discrepancies? Please describe your opinion and reasons as in detail and clearly as possible.

- Require designers to pay for their discrepancies.
- Don't grab plans that have been laying on the shelf for 18 years, blow the dust off them and hold a letting based on them.
- Have complete and accurate plans prior to construction. If not possible, then owners are more proactive in resolving issues at the beginning of the construction phase. Take the initiative to get changes resolved.
- Digital information from the owner, designer.
- Increasing the resolution of the design survey would reduce the frequency of the problem, however, the only savings would be a time associated with the redesign (the grade is what it is). The need for a wall or a permit will be revealed either through design survey or construction survey, so there are no real cost savings to construction. Reduce time between Resource Delineation and Construction to reduce problems from stream migration.
- Stop using Geographic Information System (GIS) to determine existing conditions. Field run cross sections to find the actual ground. Any tie-in should be surveyed so that the design engineer can adjust profiles for best fit.
- Better quality control during the design process. Better use of 3D modeling. Designers need to have field experience. Many cannot evaluate a design for constructability.
- Have the survey redone prior to the final field plan review.
- Everyone should work on the same live data instead of working on different copies of different versions of the data.
- Verify topographic survey. Review proposed design grades for errors and inconsistencies.
- Pre-construction is where we are focusing first. We are working on fixing errors with a statistical confidence report provided by the surveyor for existing topography and control sheet. This will be given to the contractor to give it more confidence in what it is provided.
- A best possible way to reduce discrepancies is either addendum prior to bid or value engineering if possible.
- Survey work during design is inaccurate too many times.
- Moving toward a 3D model for designers (which are now doing) such that grades can be reviewed for accuracy, checked by the contractor (quality control: QC) and finally checked by the owner (quality assessment: QA).
- The electronic survey backed up by field survey verification. The electronic survey will produce an elevation by digital terrain model (DTM) but how far are the points apart? Did they pick up the edge of pavement elevation and assume a constant cross fall or was a turn lane added with a different cross slope that was not picked up?

- Better understanding between the people involved in the design and construction phases. More accurate 3D models in intersection areas. More experienced surveyors performing construction stakeout and original topographic surveys.
- Syncing of all materials and thus maintaining one master information for everyone.

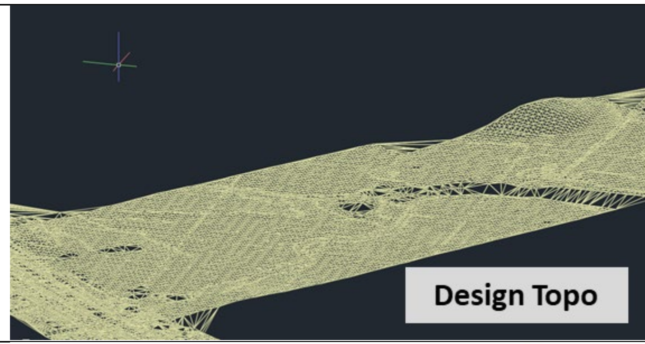
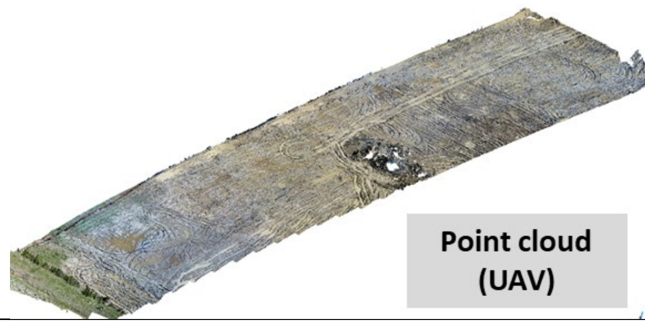
Q13 - What devices have you used to control the vertical alignment in grading process? Select all the items as they apply to you.



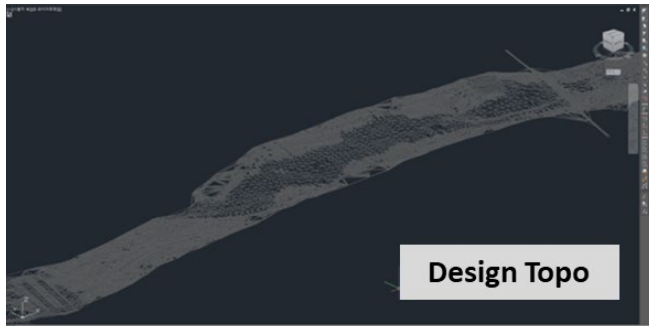
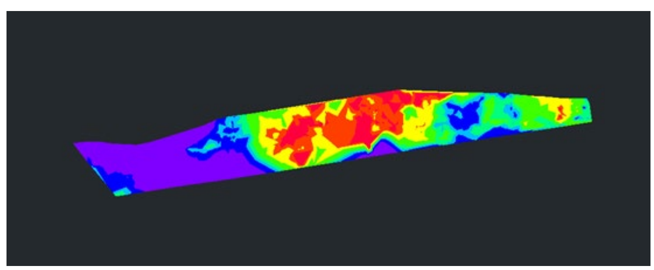
Q14 - If you have anything to share with research team besides the above questions, please feel free to leave your thoughts, ideas or opinions below.

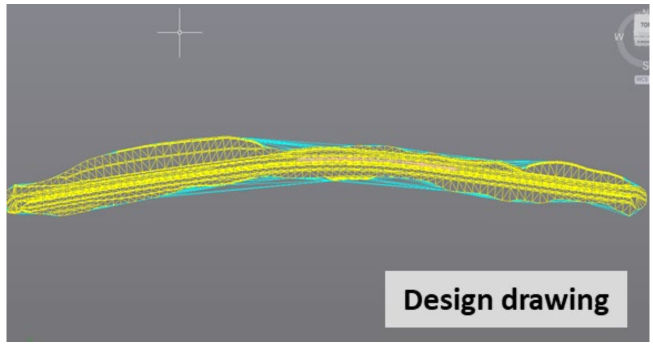
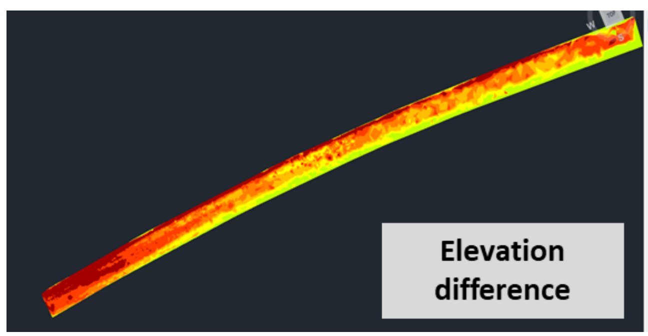
- The accuracy of the design is only as good as the accuracy of the pre-design. If the predesign includes bad data, then there will be discrepancies when construction time comes.
- There are a lot of services offered for drone photogrammetry. From my experience, this has been effective for surveying aggregate stockpiles in small batch plants. However, the technology is unreliable for surveying large grading operations to provide accurate volumes. Example: We imported appx. 50,000 CY (based on truck counts) into a much-defined area, and ran cut to fill of 150,000 CY (based on truck counts) within the same area. Upper Limit of shrinkage was probably 20%. The drone flights said we had exported 150,000 CY from the area.
- From an actual conversation with DOT personnel, they say the contractor is responsible for best fit. However, as a contractor, we spend a ton of time studying how to fix design errors and then have spent more time providing data and explaining to the DOT the issues. There is always a cost for this. It is my opinion the contractor should be about building the job and not designing. I truly believe that the DOT, for the most part, isn't getting their monies worth from the design engineers. That's not to say design engineers aren't doing a good job. It's more about using data that isn't precise enough (GIS) to bid or build by.
- Most discrepancies are a result of insufficient topo data and unknown soils. Soil reports provide insight into initial grading and site prep.
- We are moving to use 3D models as the legal document for projects. We are trying to improve our process to reduce or eliminate these issues in the future.
- Teach your students not only the computer way to do things but also the field way to do things. And to verify field data to make sure it is correct and take a few conformation shots with a level to confirm computer data taken by electronics.

APPENDIX C: MODELING AND VISUALIZATION RESULTS

<table>
<tr><th colspan="2">STA 100 – 130 (Cleared surface)</th></tr>
<tr><td>As-designed topo model</td><td>
</td></tr>
<tr><td>As-built point cloud</td><td>
</td></tr>
<tr><td>Elevation differences</td><td>The research team could not access to the field because of the ground conditions. The field only allowed the entry of construction equipment. The research team visited the site three times, but the field was always wet as shown in the image below. For this reason, the research team could not measure ground targets installed on the field for geo-referencing. The team only collect the dense point cloud with a drone without ground control points, which makes a great difference.


<An aerial image on STA 100-130></td></tr>
<tr><td>Discrepancy details</td><td>N/A</td></tr>
</table>

STA 200 – 230 (Cleared surface)	
As-designed topo model	
As-built point cloud	
Elevation differences	
Discrepancy details	- Max.: 35.80’ - Min.:-10.80’ - Average: 0.38’ - Volumes o Cut: 66,881 Cu. Yd. o Fill: 79,946 Cu. Yd. o Net: 13,065 Cu. Yd.

<table>
<tr><th colspan="2">STA 200 – 230 (Graded surface)</th></tr>
<tr><td>As-designed topo model</td><td>
</td></tr>
<tr><td>As-built point cloud</td><td>
</td></tr>
<tr><td>Elevation differences</td><td>
</td></tr>
<tr><td>Discrepancy details</td><td>

- Max.: 0.873’
- Min.: -2.352’
- Average: -0.325’
- Volumes
    - Cut: 18.798 Cu. Yd.
    - Fill: 1.222 Cu. Yd.
    - Net: 17.576 Cu. Yd. (cut)

</td></tr>
</table>